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STUDY AND EVALUATION OF V/STOL GROUND-BASED SIMULATION TECHNIQUES FOR THE X-22A AIRCRAFT

By

Jerome L. Michaels

June 1969

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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DEPARTMENT OF THE ARMY
HEADQUARTERS US ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

This report has been reviewed by the U. S. Army Aviation Materiel Laboratories and the Human Engineering Laboratories. The work, which was performed under Contract DAAJ02-67-C-0049, comprised the study of various kinds of simulators to determine their capability to produce data representative of flight for V/STOL aircraft. The resulting data were compared and correlated with flight data from the same aircraft (the X-22A). The correlations were based on a comparison of pilot ratings, pilot comments, and dynamic response time history data for comparable flight tasks in hover and transition.

The report is published for the dissemination and application of information and the stimulation of ideas in the area of simulation technology, with emphasis on handling qualities research.

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STUDY AND EVALUATION OF V/STOL GROUND-BASED SIMULATION TECHNIQUES FOR THE X-22A AIRCRAFT

Bell Aerosystems Company Report No. 7356-927001

By

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Prepared by

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for

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FORT EUSTIS, VIRGINIA

ABSTRACT

Three types of ground-based simulators of the X-22A aircraft are evaluated and compared with actual flight. Simulator types employed were a fixed-base simulator with linearized equations of motion, a fixed-base simulator with non-linearized equations of motion, and a moving-base simulator with linearized equations of motion. Evaluations are based on comparisons of pilot ratings, pilot comments, and dynamic response time history data. Data comparisons are interpreted and discussed in terms of significant factors such as simulator type, complexity, and physical and psychological cues.

Several correlations among the different simulators and flight are developed in terms of numerical pilot ratings of specific flight conditions and tasks. These pilot rating correlations provide a basis for projecting flight characteristics from results obtained with the simulator types evaluated. Relative capabilities and limitations of the various simulators to represent flight and minimum standards of adequacy for specific tasks are also established for hover and transition.

FOREWORD

This work was sponsored by the United States Army Aviation Materiel Laboratories (USAAVLABS) as part of a continuing long-range program to obtain a better understanding of various kinds of simulators and to determine their capability to produce data representative of the simulated aircraft in flight. This report documents the work performed under Contract DAAJ02-67-C-0049 (Task 1F162204A14233) by the Integrated Systems Engineering Department of Bell Aerosystems Company of Buffalo, New York, during the period from May 1967 to August 1968.

Mr. R. P. Smith of USAAVLABS monitored the technical aspects of the program, which was performed by Messrs. J. L. Michaels and H. G. Streiff of Bell Aerosystems Company. The value and scope of the program was expanded immeasurably by the willing cooperation and assistance of the X-22A project personnel and pilots, who helped to expedite the initial search for flight data, participated in the simulation effort, and always arranged to be available for consultation. Special appreciation is expressed to the pilots (Lieutenant Commander W. Davies, USN; Major I. W. Rundgren, USA; Major J. G. Basquez III, USAF; Lieutenant D. L. Green, USN; and Lieutenant W. R. Casey, USN), whose enthusiastic participation gave the data correlations added breadth and quality. Special appreciation is also expressed to personnel of the Full Scale and Systems Research Division and the Simulation Sciences Division of the NASA Ames Research Center for their efforts on behalf of this program.

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LIST OF SYMBOLS

General Notation

b	Reference span
$\bar{c}$	Reference chord
CG	Center of gravity
C_ℓ	Rolling moment coefficient
C_{ℓ_p}	Rolling moment coefficient derivative with respect to roll rate
C_{ℓ_r}	Rolling moment coefficient derivative with respect to yaw rate
C_m	Pitching moment coefficient
C_{m_q}	Pitching moment coefficient derivative with respect to pitch rate
C_n	Yawing moment coefficient
C_N	Duct normal force coefficient (two ducts)
C_{n_p}	Yawing moment coefficient derivative with respect to roll rate
C_{n_r}	Yawing moment coefficient derivative with respect to yaw rate
C_T	Airplane thrust coefficient (four ducts)
C_x	Axial force coefficient
C_Y	Side force coefficient
C_{Y_p}	Side force coefficient derivative with respect to roll rate
C_{Y_r}	Side force coefficient derivative with respect to yaw rate
C_z	Normal force coefficient
D	Diameter of duct
$f(\ )$	Function of quantity in brackets

g	Acceleration due to gravity
h	Altitude
I_x	Moment of inertia about the x-axis
I_y	Moment of inertia about the y-axis
I_z	Moment of inertia about the z-axis
I_{xz}	Product of inertia
L	Characteristic length of turbulence or rolling moment (positive right wing down)
L_p	Roll damping derivative
L_r	Rolling moment derivative with respect to yaw rate
L_v	Rolling moment derivative with respect to lateral velocity
L_δ	Rolling moment derivative with respect to control input
M	Pitching moment (positive nose up)
M_q	Pitch damping derivative
M_u	Pitching moment derivative with respect to longitudinal velocity
M_w	Pitching moment derivative with respect to normal velocity
M_δ	Pitching moment derivative with respect to control input
m	Mass
n_z	Normal load factor
N	Yawing moment (positive nose right)
N_p	Yawing moment derivative with respect to roll rate
N_r	Yaw damping derivative
N_v	Yawing moment derivative with respect to lateral velocity
N_δ	Yawing moment derivative with respect to control input

p	Roll rate (positive right wing down)
q	Pitch rate (positive nose up)
q	Dynamic pressure
q_T	Transformed dynamic pressure
R_c	Cross range distance
R_g	Down range distance
r	Yaw rate (positive nose right)
S	Reference area
T	Thrust
$\frac{dT}{d\beta}$, T_β	Propeller blade effectiveness parameter
U	Total velocity along the longitudinal body axis
u	Incremental longitudinal velocity measured from U_o(positive forward)
V	Free-stream velocity
$\overline{V}$	Mean wind velocity
v	Lateral velocity (positive right)
w	Normal velocity (positive down)
w_g	Gust velocity
X	Longitudinal force (positive forward)
x	Longitudinal distance (positive forward)
x_{AX_F}	Perpendicular distance between forward duct thrust vector and airplane CG
x_{AX_A}	Perpendicular distance between aft duct thrust vector and airplane CG
x_{N_F}	Perpendicular distance between forward duct normal force vector and airplane CG
x_{N_A}	Perpendicular distance between aft duct normal force vector and airplane CG

X_u	Longitudinal force derivative with respect to longitudinal velocity
X_w	Longitudinal force derivative with respect to normal velocity
Y	Lateral force (positive to right)
Y_p	Side force with respect to roll rate
Y_r	Side force derivative with respect to yaw rate
Y_v	Side force derivative with respect to lateral velocity
y	Lateral distance (positive to right)
y_A	Spanwise distance from the aircraft centerline to the aft duct centerline
y_F	Spanwise distance from the aircraft centerline to the forward duct centerline
Z	Normal force (positive down)
Z_u	Normal force derivative with respect to longitudinal velocity
Z_v	Normal force derivative with respect to lateral velocity
Z_w	Normal force derivative with respect to normal velocity
$\ddot{Z}_{\delta_T}$	Thrust control gradient
z	Vertical distance (positive down)

Greek Symbols

α	Angle of attack
β	Propeller blade angle (positive for positive thrust) or angle of sideslip (positive for right sideslip)
γ	Flight path angle (positive in climb)
δ	Control deflection (identified by subscript)
ζ	Damping ratio
θ	Pitch attitude angle (positive nose up)
λ	Duct angle measured with respect to the airplane reference waterline
π	Pi
ρ	Density
σ_g	rms gust velocity
τ	First-order response time constant
ϕ	Bank angle (positive right wing down)
ψ	Yaw angle (positive nose right)
ω	Frequency

Subscripts

A	Analog
a	Aileron
Aero	Aerodynamic
C	Collective
c	Control
DC	Digital Computer
Δ	Increment
e	Elevon, exit
F	Flaps
G.E.	Ground effect
grd	Ground
max	Maximum
MP	Military power
o	Initial condition
ps	Pitch stick
r	Rudder
rp	Rudder pedal
rs	Roll stick
RY	Roll-yaw
SAS	Stability Augmentation System
T = 0	Thrust equal to zero
T_c	Throttle control

Abbreviations

ALMB	Ames Linearized Moving Base
BLFB	Bell Linearized Fixed Base
BHFB	Bell Hybrid Fixed Base
CRT	Cathode Ray Tube
DOF	Degrees of Freedom
FLT	Flight
F.O.P.	Fixed Operating Point
HP	Horsepower
IFR	Instrument Flight Requirements
IGE	In Ground Effect
kn	Knots
LORAS	Low Range Air Speed
LT	Left
MPE	Military Preliminary Evaluation
OGE	Out of Ground Effect
PIO	Pilot-Induced Oscillation
RCR	Revised Pilot Rating
RT	Right
SAS	Stability Augmentation System
VFR	Visual Flight Requirements
VSI	Vertical Speed Indicator
VSS	Variable Stability System
V/STOL	Vertical Short Takeoff and Landing
VTO	Vertical Takeoff

INTRODUCTION

In recent years the ground-based flight simulator has gained increasing acceptance and recognition as an effective and low-cost means of solving a large variety of engineering design and handling qualities research problems for piloted vehicle developments. Simulator usage has grown especially fast in the field of V/STOL aircraft, where the problems of flight dynamics are multiplied by the continuously variable aerodynamics and control derivatives in the speed range between hover and conventional flight. Essentially all V/STOL programs now regularly employ simulators of various types as design and training aids. Simulator evaluations carried on in conjunction with aircraft development are being used to avoid costly downstream modifications, by uncovering and solving potential problem areas before commitments to detail design or fabrication are made. Simulators have also become recognized as powerful research tools for systematic study of the varied human engineering problems related to the establishment of flight control system design requirements and handling qualities criteria.

While simulators are being ever more widely used for the purposes mentioned, very little systematic information has yet been generated to establish categorically the realism or validity of different simulator types. The various published studies in the literature are mostly independent investigations which report their findings as parametric data trends and relative merit evaluations, without relation to a frame of reference based on actual flight. In the design process, the results of such studies are of necessity applied on an incremental rather than an absolute basis, and the true dynamic handling characteristics remain in question until finally established by flight test. There is, therefore, a definite need for a quantitative determination of the degree of fidelity of the various simulator types with respect to actual flight, and for the definition of their capabilities and limitations when used in their customary engineering design, research, and training applications.

The present study is part of a long-range program to fill this need by developing sufficient data to catalog the many types of ground-based simulators according to their capabilities and limitations for representing the true flight characteristics and handling qualities of aircraft. The work reported is based on comparisons of data from simulations and flights of the X-22A V/STOL research aircraft. Objectives of the study were to make comparisons and correlations of simulator results with flight for as wide a range of flight and simulator variables as possible from existing data, to generate additional data as appeared to be necessary, and to expedite the completion of this task. The study results provide a broad base of data and techniques aimed at achieving the stated goals.

Direct comparisons of pilot opinion data and dynamic response data with actual flight test results are presented for three ground-based simulator types, for a comparable series of pilot tasks, in both the hover and the transition flight regimes. Data comparisons are interpreted and discussed in terms of the significant factors, which include simulator type, complexity, dynamic response characteristics, pilot sensitivity, physical environment, and physical and psychological cues.

Ground-based simulators evaluated in this study are:

Bell Linearized Fixed-Base Simulator (BLFB)

Bell Hybrid Fixed-Base Simulator (BHFB)

Ames Linearized Moving-Base Simulator (ALMB)

Wherever possible, the above simulators have been compared with each other and with flight results for the following series of pilot tasks:

Hover Task Category

Height Control
Attitude Control
Forward Translations
Lateral Translations
Hovering Turns
Hover in Ground Effect
Hover Dynamics

Fixed Operating Point Transition Task Category

Longitudinal Trim and Static Stability
Longitudinal Long-Period Dynamic Mode
Longitudinal Short-Period Dynamic Mode
Directional Static Stability
Banked Turns
Lateral-Directional Dynamic Mode
Lateral Control Response

Continuous Transition Task Category

Conversions
Reconversions

In several instances, the above tasks were evaluated for additional variables to provide insight into particular problem areas and to aid in the interpolation and extrapolation of results from one test point to another. These additional variables include:

Stability Augmentation Level
Reduced Degrees of Freedom
Motion Scaling Effects

DESCRIPTION OF DATA SOURCES

FLIGHT DATA SOURCES

Physical Description of the X-22A Aircraft

The X-22A is a V/STOL research aircraft in the 15,000-pound weight class. Flight evaluations to date have logged over 67 hours of hover and transition in more than 150 flights. A photograph of the aircraft in hovering flight is shown in Figure 1. Important configuration features of the design include:

Ducted propeller thrust units
Dual tandem configuration arrangement
Duct rotation in transition
Control by elevons and propeller blade angles

Two separate systems are provided for thrust control. Data evaluated in this report were obtained using the collective thrust control mode, which operates by a collective control stick that controls propeller blade angle directly. With this system, the engine control levers are used to select a power turbine governor rpm, which regulates the power turbine output, as in conventional helicopters. The total collective stick motion available is 30°, which requires approximately 9 inches of vertical travel at the pilot's grip. Thrust vector rotation for transition is accomplished by rotating the ducts, which are operated by a thumb switch located on the thrust control.

Attitude control is obtained from two independent sources of control force:

Differential deflection of aerodynamic flaps located in the exit planes of the ducts.

Differential thrust produced by variable propeller blade angle.

The attitude controls are operated by a conventional stick and rudder pedals. In the different flight regimes, attitude control is maintained by appropriate combinations of elevon and propeller blade angle deflections, which are phased as a function of duct angle to minimize undesirable control coupling (e.g., roll due to yaw control or yaw due to roll control) and to provide desirable handling qualities.

Pitch and roll stick force gradients are provided by an artificial feel system, which increases the gradients with increasing airspeed. Pedal forces are primarily frictional, with simple mechanical spring forces available at the option of the pilot.

Figure 1. X-22A in Hovering Flight.

The primary aircraft control system includes a dual stability augmentation system (SAS), installed in series, with limited authority which provides simple rate damping in pitch, roll, and yaw. This system is used for the lower conventional flight speeds and is phased out at the higher cruise speeds. At the option of the pilot, either or both SAS channels can be switched off.

The cockpit flight instrumentation consists of two identical groups of basic flight instruments located directly in front of each pilot and on either side of an instrument cluster which monitors individual engine performance. Flight parameters displayed in the flight instrument groups include airspeed, duct angle, pressure altitude, radar altitude, instantaneous rate of climb, attitude reference, situation display, propeller rpm, and time. Engine instruments present turbine rpm, torque, and exhaust gas temperature.

Flight Test Program Status

At the beginning of the study, the X-22A development and demonstration of flying qualities program had a total accumulated flight time of 18 hours for 46 flights. These flights had all been performed in the collective thrust control mode, and the tests performed satisfied a major part of the hover and transition flight data requirements for the first Military Preliminary Evaluation (MPE). This group of tasks and flight conditions provided the initial basis for the review and search for comparable simulator data. Additional data acquired as the study progressed increased the body of applicable data. A significant and unexpected increase in the amount of useful data available occurred as a result of the first Military Preliminary Evaluation (MPE-1). This evaluation was conducted by a team of military test pilots and engineers who planned and performed a series of repeatable flight tasks at representative test points spanning the hover and transition flight envelope. These tests reevaluated much of the earlier data, expanded its usefulness, and supplied additional documentation of pilot rating and time history data in both hover and transition. The incorporation of the MPE-1 data with the previous flight results provided a much broader basis for comparing simulators with flight.

At the end of the study, the development and demonstration of flying qualities phase of the flight test program was essentially complete. Accumulated flight time exceeded 67 hours; these figures included 72 flights and 32 hours in the collective control mode.

A representative sample of these data covering the flight envelope has been published in Reference 1.

SIMULATOR DATA SOURCES

Data accumulated in various stages of the X-22A development were obtained from three separate and essentially different X-22A simulations, covering both the hover and the transition flight regimes. After an initial review of the data, the three simulations were set up and rerun to provide additional and directly comparable test points.

The scope, original design objectives, and description of these simulations are contained in this section. Mechanization details and equations of motion are presented in Appendix I.

Bell Linearized Fixed-Base Simulation (BLFB)

As part of the X-22A program, a linearized fixed-base analog simulation was set up in 6 degrees of freedom (DOF) to evaluate the hover flight regime and to assist in the functional design of the cockpit and control systems. The BLFB simulation was mechanized so that it could be operated in reduced degrees of freedom and at fixed operating points in transition, as desired. Its cockpit, flight controls, and information displays were later used for the BHFB simulation. Results obtained with this simulation provided a rational basis for choosing suitable control configurations and selecting design values for various system parameters, and gave added insight into the aircraft flight behavior in hover through firsthand pilot experience. The many design areas evaluated with this simulation include:

Height control with alternate modes of thrust control (e.g., throttle mode and collective stick mode).

Effect of thrust response time lag.

Height and attitude control power and damping requirements.

Effect of attitude and thrust control couplings.

Hover translation and attitude control characteristics.

Stability augmentation levels.

Control force gradients and breakout force levels.

Control force trim rates.

Cockpit flight control locations and functions.

Additional simulations performed for this study using this simulator include 3-DOF longitudinal operation (X, Z, θ) and 4-DOF lateral-directional operation (Z, Y, ϕ , ψ) at selected fixed operating points and speed-duct angle combinations in hover, in addition to extensive 6-DOF investigations in hover and at fixed operating points in transition.

Bell Hybrid Fixed-Base Simulation (BHFB)

The 6-DOF hybrid simulation was developed in the X-22A program primarily to explore the transition flight regime for potential problem areas. The program permits continuous flight over the entire flight envelope from VTO through transition, to conventional flight, and back again to hover and landing, with no loss in fidelity due to small-angle approximations or assumptions of linearized aerodynamics that are often made to simplify mechanization problems.

The BHFB simulation was used extensively as a design tool in developing good stability and control, feel and trim, and handling qualities characteristics, and in evaluating various flight control techniques and procedures throughout the V/STOL regime. In the course of these studies, the pilots received much useful preflight training and developed a high degree of confidence in flying the X-22A airplane.

This simulation was subsequently used to evaluate various aspects of aircraft behavior experienced in flight, and it continues to be used as a pilot training aid. Some of the design areas that this simulation was used to investigate include:

Height control parameters in hover.

Development of takeoff, landing, and thrust rotation techniques.

Control power and damping requirements and design levels in transition.

Stick and pedal control force levels in transition.

Lateral-directional control coupling evaluation in transition.

Effects of control system response characteristics on handling characteristics.

Piloted maneuvers and evaluation of stability and control characteristics in all flight regimes.

Rate-of-descent envelopes and safe emergency-landing footprints for various thrust-to-weight ratios and duct rotation rates.

Development of optimum flight control system phasing and transition flight procedures.

Piloted analyses of random control system failures.

A photograph of the fixed-base cockpit station is shown in Figure 3. It consists of a pilot seat with a powered height adjustment, two side consoles, floor-mounted hydraulically powered flight controls, and a forward instrument and information display panel. This cockpit is generally representative of the X-22A and was used for both the BHFB and the BLFB simulations.

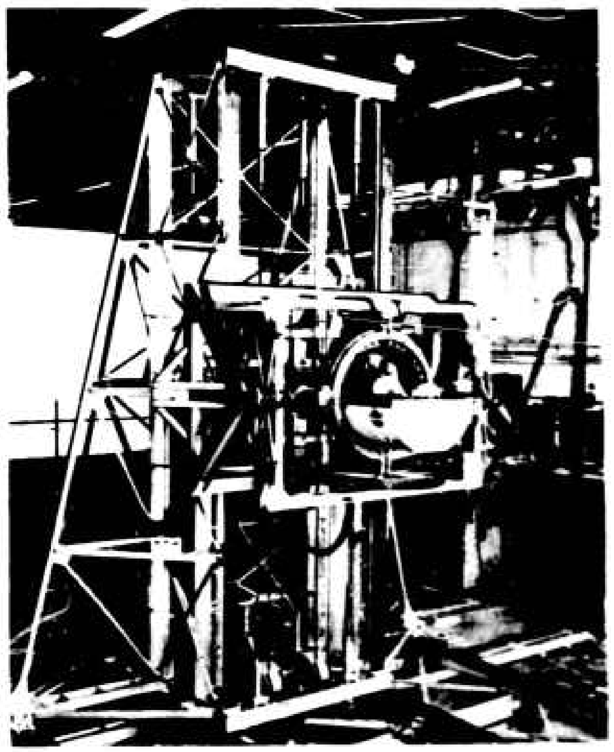
The additional BHFB simulator data used in this study were taken from concurrent X-22A pilot training simulations performed in connection with the MPE-1 flight evaluation. Consequently, control over the quality of the data and the precise definition of pilot tasks, required to make proper comparisons with other simulator data according to the objectives of this study, were secondary considerations which were subordinated to the primary pilot training objectives. Nevertheless, useful ratings, comments, and time history data were obtained in both hover and transition.

Ames Linearized Moving-Base Simulation (ALMB)

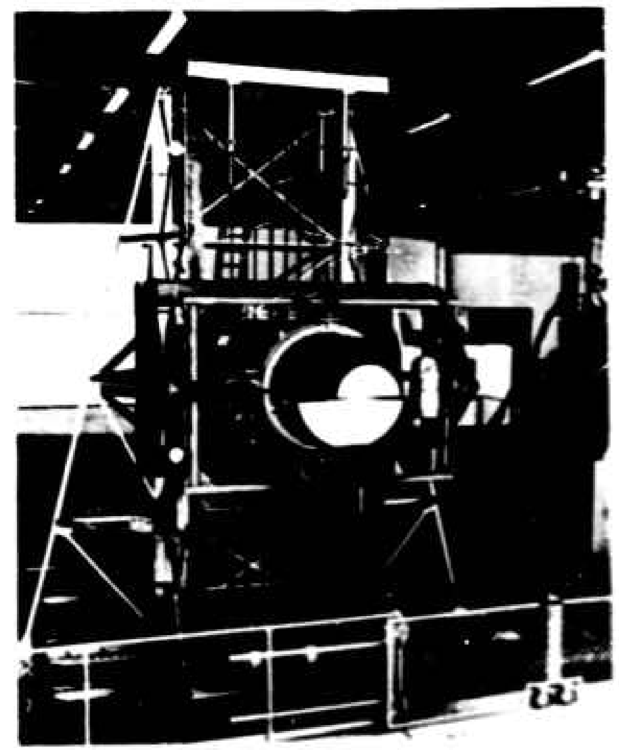
Prior to the first flight of the X-22A, a relatively brief linearized hover program was conducted on the Ames 6-DOF moving-base simulator with the primary objective of training two X-22A test pilots. This program evaluated the pitch, roll, yaw, and height control handling characteristics in hover for thrust control parameters representing both the collective stick and the throttle control modes. Several visual hover and air taxi flight tasks were performed at FULL, 1/2, and NO SAS.

A photograph of the simulator installation for both VFR and IFR operation is shown in Figure 2. The pilot station or cockpit is installed in a cab which is mounted on tracks and gimbals providing motion in 6-DOF, any or all of which can be locked out as desired. Simulator travel is limited to an 18-foot flight cube that is partially below ground level. Angular excursion limits are $\pm 40^{\circ}$ about all three axes. Linear and angular acceleration capability exceeds the ranges normally encountered or anticipated by the X-22A in hover.

The pilot station consists of a fixed pilot seat, conventional flight controls, and a forward instrument panel. The simulator is normally flown under VFR conditions with the field of view limited only by the ceiling, side walls, and sometimes the floor of the hangar when the region of the flight cube below ground



VFR



IFR

Figure 2. ALMB Flight Simulator.

level is used. For the additional simulations related to this program, the instrument panel was modified to represent as closely as possible the instrumentation provided in the BLFB and BHFB simulators, and a collective stick was substituted for the throttle-type thrust control previously used. Photographs of the pilot station showing comparisons of the flight controls and the instrument panels of the fixed- and moving-base simulators are shown in Figures 3 and 4.

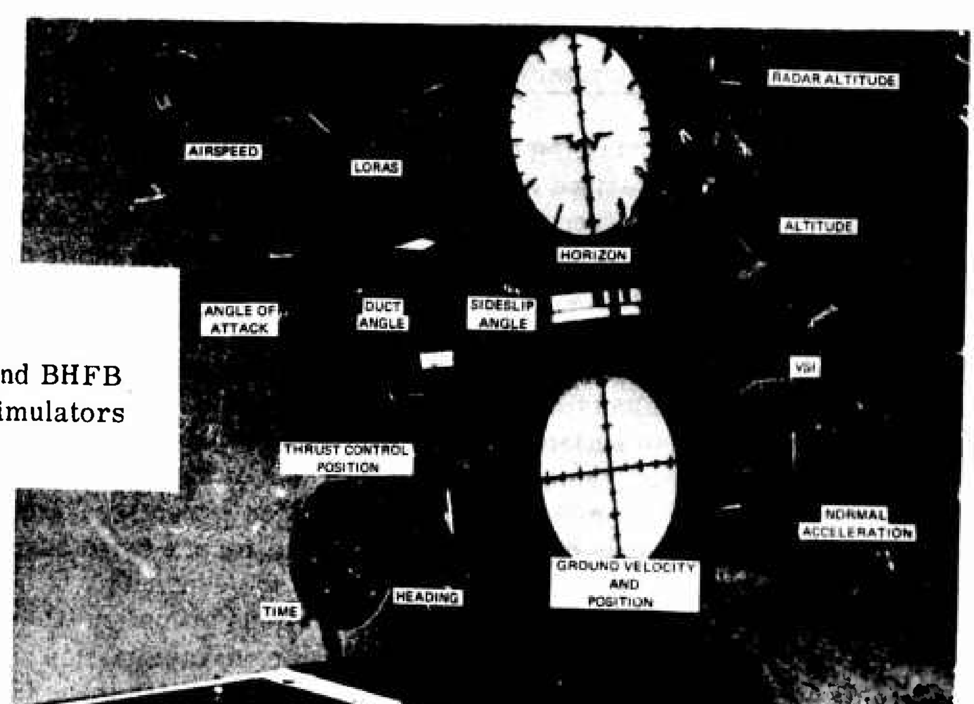
Additional ALMB simulations performed as part of this study were mechanized using the updated hybrid computer capability with linearized hover derivatives. The scope of the additional data obtained includes evaluation of ground effects, winds, gusts, and stability augmentation level for a series of simulated hover tasks.

ALMB Flight Simulator

BLFB and BHFB Flight Simulator

Figure 3. Comparison of Simulator Flight Controls.

ALMB Flight Simulator



BLFB and BHFB Flight Simulators

Figure 4. Comparison of Simulator Instrument Panels.

METHODS OF ANALYSIS

A rationale was established early in the program to facilitate the initial data review and comparison. As the review progressed, methods and analytical techniques were devised to guide the review and to perform the compilation, acquisition, correlation, and analysis of data. The rationale, methods, and techniques developed are set forth and discussed in this section.

RATIONALE, METHODS, AND TECHNIQUES

The purpose of the initial data review phase was to establish the scope of the existing data, to identify common parameters, and to develop meaningful categories for the data comparisons. The categories of data reviewed included time histories of flight parameters, pilot rating data, and pilot comments.

The basic approach taken was to search out and compile steady-state and dynamic response time history data, pilot ratings and comments from each different simulation and from flight, and to relate these for comparable values of the significant variables, which include flight conditions, flight task, aerodynamic and systems parameters, and aircraft physical parameters. Differences in simulator and flight results were then interpreted and discussed in terms of inherent differences in one or more elements of the simulations, which include simulator type, complexity, and physical and psychological cues.

Factors Affecting Simulator Realism and Fidelity

The difficulty of comparing handling qualities of ground-based simulators with flight is best placed in perspective by considering the almost overwhelming variety of factors that require representation. First, for low-disc-loading, tilt-thrust V/STOL aircraft such as the X-22A, the low-speed aerodynamic derivatives, which are usually represented by linear functions of aircraft attitude, are actually nonlinear functions that also vary as the aircraft changes configuration between hover and conventional flight. Such aircraft also experience large aerodynamic power effects. Control system functions in transition generally require phasing to maintain the effectiveness of the flight controls. Hence, the control functions are also complex functions of speed, configuration, control deflection, and power, making the representation of control power, control sensitivity, control cross-coupling, and control forces more difficult. In the X-22A, the levels of stability augmentation and the sensitivity of the propulsion system control also vary in transition. Equations of motion that simulate transition should accommodate both the nonlinear characteristics and the variations in configuration. The degree of accuracy to which these factors are represented, and the number and nature of simplifying approximations made, affect the realism and degree of fidelity of the mathematical model in

representing the static and dynamic characteristics of flight; the more exact the model, the more complex and expensive the simulation. For many design purposes, simplifications that minimize equipment requirements can usually be justified. Such simplifications include small-angle approximations, linearization of aerodynamic stability and control derivatives at specific operating conditions, reduced degrees of freedom, and fixed-base simulations.

Other factors affecting simulator realism and fidelity are related to the type and nature of the cockpit instrumentation. These factors are particularly important for IFR flight conditions or in fixed-base simulators, where the pilot receives the necessary flight information and cues from visual presentations of key parameters which are normally perceived over wider ranges by a combination of visual, kinesthetic, aural, and vestibular sensations; the flight envelope of useful simulation is directly related to the inherent limitations of the flight information presented, independent of the mathematical model.

Still other factors affecting simulator realism and the fidelity of dynamic response are related to moving-base simulation. These factors include the physical limitations imposed on the linear and angular displacements, the lack of realistic visual cues for higher speed applications, and the introduction of extraneous cues associated with the operation of the motion equipment. These factors introduce perceptual limitations in the form of unrealistic visual, aural, vestibular, and kinesthetic cues that can evoke distorted pilot reactions and negate some of the apparent advantages of moving-base simulations in certain applications.

Categories of Factors and Tasks

The many factors affecting the data were resolved into two broad but essentially different categories: factors in common and variable factors (itemized in Table I). The first category contains those factors that must be controlled to represent the aircraft flight behavior properly; it includes aerodynamic parameters, aircraft physical parameters, most simulated aircraft system variables, pilots, flight conditions, and flight tasks. The second category contains those less controllable factors that may or may not differ, depending on individual simulator characteristics; it includes most elements of the simulation, such as simulator type, mechanization of equations of motion, degrees of freedom, information displays, physical environment, and physical and psychological cues. Some of these factors can be controlled to an extent during simulator design to improve the realism and uniformity between different simulations of a particular aircraft, but most require interpretation in terms of the individual simulator type. In making the initial data review all of these factors were kept in mind, but the common factors category was foremost, since a significant discrepancy there would jeopardize the data comparisons.

TABLE I. FACTORS AFFECTING SIMULATION FIDELITY	
Factors in Common	Variable Factors
Aerodynamic Parameters	Simulator Type
Aircraft Physical Parameters	Equations of Motion
Control System Parameters	Degrees of Freedom
Feel System Parameters	Information Displays
Propulsion System Parameters	Physical Environment
Pilots	Physical and Psychological Cues
Flight Tasks	
Flight Conditions	

Factors in Common

In the selection and generation of the comparable data in this program, factors in this category were carefully controlled. As a result, there is an abundance of commonality among pilots, flight conditions, flight tasks, aerodynamic stability and control parameters, and system characteristics. The basis of comparison is given in this section. All aerodynamic and system parameters are based on the final preflight estimated characteristics of the X-22A, published in References 2 through 8. All simulator data are based on nominal estimated values of the final aircraft physical parameters, as given in Table II.

TABLE II. AIRCRAFT PHYSICAL PARAMETERS	
Weight	14,700 lb
Rolling Moment of Inertia, I_x	15,000 slug-ft^2
Pitching Moment of Inertia, I_y	32,000 slug-ft^2
Yawing Moment of Inertia, I_z	45,000 slug-ft^2
Product of Inertia, I_{xz}	4,650 slug-ft^2
Center of Gravity, Station	312 in.
Center of Gravity, Waterline	138.7 in.

Aerodynamic derivatives used for the linearized simulations, BLFB and ALMB, are listed in Table III. These values were developed from the BHFB nonlinear data tables as equivalent linear values at the flight conditions noted.

Estimated FULL SAS levels provided in the X-22A are compared in Table IV to the levels used for FULL SAS in the various simulation programs. Variations ranging from FULL SAS down to NO SAS were generally evaluated in each program to provide a convenient means of interpolating or extrapolating the data to a common SAS level. This refinement was necessary because of differences in the FULL SAS levels of the existing simulator data, which came about as the result of periodic reassessments of pilot-recommended SAS levels with increasing flight experience in the aircraft. These differences in SAS have been accounted for in interpreting and summarizing the final results, but the detailed data compilations presented in Appendix II are uncorrected.

TABLE III. AERODYNAMIC DERIVATIVES USED FOR THE LINEARIZED SIMULATIONS

Derivative (Body Axes)	Hover (α = 3.5°)	F.O.P. Transition λ =30°, V = 80 kn (α = 0°)	Units
X_u	-0.233	-0.164	1/sec
X_w	0	-0.072	1/sec
Y_v	-0.245	-0.264	1/sec
Y_p	-0.774	-1.098	(ft/sec^2)/(rad/sec)
Y_r	0	0.842	(ft/sec^2)/(rad/sec)
Z_u	0.00275	-0.253	1/sec
Z_v	0.00275	0	1/sec
Z_w	-0.098	-0.525	1/sec
M_u	0.0224	-0.00326	(rad/sec^2)/(ft/sec)
M_w	0	-0.00834	(rad/sec^2)/(ft/sec)
M_q^*	-0.13	-0.57	1/sec
L_v	-0.056**	-0.044	(rad/sec^2)/(ft/sec)
L_p^*	-0.30	-1.873	1/sec
L_r	0.177	0.727	1/sec
$L_{\delta rp}$	0	0.033	(rad/sec^2)/in.
$L_{\delta rp/V}$	0	-0.00337	rad/(ft-sec-in.)
N_v	0.0006	0.006	(rad/sec^2)/(ft/sec)
N_p	0	-0.025	1/sec
N_r^*	-0.148	0.25	1/sec
$N_{\delta rs}$	0	0.0192	(rad/sec^2)/in.
$N_{\delta rs/V}$	-0.0006	-0.0005	rad/(ft-sec-in.)

* Values given are basic airframe.

** This value was used in the BLFB and ALMB. A value of -0.0394 was used in the BHFB.

TABLE IV. COMPARISON OF FULL SAS LEVELS (1/sec) FOR SIMULATORS AND AIRCRAFT					
		Hover		F.O.P. Transition $\lambda = 30^\circ$, V = 80 kn	
Case	Axis	Aug	Unaug	Aug	Unaug
X-22A (Est) and BLFB	Pitch	-6.2	-0.13	-4.55	-0.67
	Roll	-5.9	-0.283	-2.1	-1.9
	Yaw	-2.1	-0.15	-2.1	-0.38
BHFB	Pitch	-3.45	-0.13	-3.0	-0.67
	Roll	-4.5	-0.283	-1.7	-1.9
	Yaw	-1.0	-0.15	-0.98	-0.38
ALMB	Pitch	-6.2 (-8.0)	-0.13	-4.55	-0.67
	Roll	-5.9 (-10.0)	-0.283	-2.1	-1.9
	Yaw	-2.1	-0.15	-2.1	-0.38

NOTE: $1/2 \text{ SAS} = \text{Unaug} + \left[\frac{\text{Aug}}{2}\right]$

Values in parentheses were used for the bulk of the ALMB program, on recommendation of MPE pilots who felt that they were more representative of the aircraft. Lower values apply to Pilot H only.

Control powers, control travel, and feel system parameters were essentially the same as the aircraft design levels for all simulations. These characteristics are compared in Table V for the hover control mode.

TABLE V. HOVER CONTROL SYSTEM PARAMETERS

			Control Force					
			Breakout (lb)			Gradient (lb/in.)		
Control Axis	Control Power	Control Motion	BLFB & BHFB	ALMB	FLT	BLFB & BHFB	ALMB	FLT
Pitch	3.40 rad/sec^2	5.6 in.	1.21	0.5	0.5	1.0	0.8	1.2
Roll	3.25 rad/sec^2	5.2 in.	1.13	0.25	0.5	1.1	0.8	1.2
Yaw	0.70 rad/sec^2	3.25 in.	3.0	2.5	5.0	0 to 5	0	0
Collective	1.35 g	9.0 in.	-	-		Optional Friction Setting		

Propulsion system thrust level, response time lag, and thrust control sensitivity were also based on final wind tunnel and systems test results for the collective control mode. These characteristics vary continuously with forward speed in transition. Selected values for hover and fixed operating point transition at $\lambda = 30^\circ$, V = 80 kn, are given in Table VI.

TABLE VI. THRUST CONTROL AND PROPULSION SYSTEM PARAMETERS (COLLECTIVE MODE)

Parameter		Hover	F.O.P. Transition $\lambda = 30^\circ$, V = 80 kn
T_{max}	lb	19,800	14,800
τ_{δ_T}	sec	0.2	0.2
$\ddot{Z}_{\delta_T}$	g/in.	0.15	NA

The list of flight conditions and flight tasks evaluated in the study was developed from an initial examination of the available flight data to facilitate a more specific search of the simulator data. The list includes only well-performed flight tasks. Incompletely documented tasks and those considered to be inappropriate to the simulations being compared are excluded. Tasks in the final list, as presented in Table VII, represent those for which data comparisons were made. All tasks are broadly covered by simulator data as a result of the existing and additional simulator programs.

TABLE VII. FLIGHT TASK CATEGORIES
<u>Hover Task Category</u>
Height Control - Holding heading
Attitude Control - Holding attitude
Translations Forward, Aft, and Laterally at Steady Altitude
Hovering Turn Performance
Hover in Ground Effect
Dynamic Flight Tasks in Hover
<u>Fixed Operating Point Transition Task Category</u>
Longitudinal Trim and Static Stability
Longitudinal Long-Period Dynamic Mode
Longitudinal Short-Period Dynamic Mode
Directional Static Stability
Banked Turns
Lateral-Directional Dynamic Mode
<u>Continuous Transition Task Category</u>
Conversions at Steady Altitude
Reconversions at Steady Altitude

Variable Factors

The nature of most factors in this category of Table I is inherent in the simulator type. Individually, they are difficult to isolate or to define in specific terms. Hence, results should be viewed on an overall basis as reflecting fundamental and inherent differences that exist between one simulator type and another or between individual simulators and flight. These variable factors can affect the data indirectly, by the sometimes subtle differences in physical and psychological cues which the pilot needs to perceive his flight situation and to perform his tasks. These cues and stimuli can stem from many sources, including cockpit motion, peripheral vision, cockpit environment, cockpit instrumentation, control forces and movements, general noise and vibration levels, and changes in sound level

as the result of pilot action, the precise definition of which is the subject of current study by a variety of organizations and individuals.

Since the breadth of this study precluded the isolation and evaluation of all of these factors individually, their impact on the results was reduced to a practical minimum by the exercise of control over the experimental design. For example, essentials of the physical environment were configured to be the same; that is, the pilot station layout and the locations, forces, and motions of the flight controls were the same in the simulators as in flight. Flight information displays and their locations were also basically the same in all simulators. Computational differences in the equations of motion among the different simulators were evaluated by an analysis of the static and dynamic responses to pilot inputs at fixed operating points, as compared to flight; selected examples are presented and discussed in Appendix III. Results of this analysis demonstrate that there is no significant influence of the differences in the mathematical models among the simulators for flight tasks performed at fixed operating points, and that responses in the simulator agree with responses in flight, within the ability of the pilot to detect a difference. Other comparisons of control positions and flight attitude from continuous transitions performed in the BHFB simulator with flight results show that the nonlinearized aerodynamics in transition were representative.

In addition, some of the variable factors were evaluated to a limited extent as independent variables to aid in understanding and interpreting the numerical pilot ratings. Relative effects of reduced degrees of freedom were evaluated independently in the BLFB simulator. Relative effects of cockpit motion were investigated by a limited evaluation of linear motion scaling in the ALMB simulator over a range from 1/10 actual to true motion. Results and implications of these brief side studies are discussed under Analysis and Discussion of Simulator Data Correlations with Flight. These foregoing measures served to materially reduce the number of unknown influences in the final results.

Pertinent details of the BLFB, BHFB, and ALMB simulators relevant to the variable factors category are presented and discussed in other sections of the report; some are under Description of Simulators, and others are in Appendix I which contains details of the equations of motion and mechanization. The various sources of physical and psychological cues and stimuli were classified into the following six categories: visual, aural, vestibular and kinesthetic, tactile, olfactory, and physical and environmental features, which are compared in Table VIII. The degree to which each of the three simulators represented the aircaft in each category is implicit in the comparisons.

TABLE VIII. COMPARISON OF SOURCES OF PHYSICAL AND PSYCHOLOGICAL CUES IN AIRCRAFT AND SIMULATORS

Category	X-22A Aircraft	BLFB and BHFB Simulations	ALMB Simulation
Visual	Visibility of horizon varies with altitude. Vertical height references available due to ground proximity and nearby objects. Peripheral vision and field of view limited by instrument panel, ducts, canopy, and door frame. Complete cockpit instrumentation.	Horizon simulated by CRT attitude display in pitch and roll. Height displayed by radar altimeter. Ground velocity and position displays and VSI, LORAS, and airspeed indicators used to compensate for lack of peripheral vision cues. Isolation screen.	Instrument presentation conformed as closely as possible to the BLFB and BHFB displays. Peripheral vision simulated to a large degree by real-world display. Some extraneous peripheral vision cues introduced by gimbal displacement. Visual cues provided by simulator travel not representative of steady forward or lateral visual flight cues except for hover.
Aural	Changes in sound level due to changes in applied power and attitude controls. General noise level masks lesser sounds. Audible vibration in certain flight regimes.	No attempt to simulate functional sounds. General sound level of operating equipment was present.	No attempt made to represent functional sounds. Unrealistic sound cues introduced by carriage motions and simulator drives.
Vestibular and Kinesthetic	All motion-related linear and angular accelerations are sensed within the confines of the cockpit and the restraints of the seat and harness	Fixed base precludes simulation of motion cues. These cues supplanted by additional visual CRT displays of pitch and roll attitude in transition, and forward and lateral velocity and position in hover.	Motion related linearized and angular acceleration cues simulated by moving base within linear and angular travel limits of simulation. Range of linear motion scaling from 1/10 to 1/1 actual evaluated for IFR.
Tactile	Control force and feel characteristics. Cockpit humidity and temperature. Aircraft vibrations.	No attempt made to simulate cockpit temperature environment of aircraft. Control feel and trim system simulated by electrohydraulic system. Representative.	Control feel system simulated by undamped mechanical bungee system. Generally representative. No attempt made to simulate cockpit temperature environment of aircraft. Some unrealistic vibration cues due to simulator mechanical drives.
Olfactory	Cockpit ventilation available. Equipment operation and malfunctional odors.	No attempt at functional or malfunctional simulation.	No attempt at functional or malfunctional simulation.
Physical and Environmental Features	General crew station layout and physical constraints. Effects of winds and gusts. Effects of ground proximity.	All significant physical constraints of cockpit station simulated. All handling qualities flight instruments simulated in same general location as aircraft. Thrust and attitude controls resemble aircraft equipment and are located as in aircraft. All control travels as in aircraft.	All significant physical constraints of cockpit station simulated. Enclosure provided for IFR tasks. Flight instrument presentation approximated BLFB and BHFB as closely as possible. Thrust and attitude controls resemble aircraft equipment and are located as in aircraft. Pitch, roll, and collective stick forces and travels as in aircraft. Rudder pedal forces and travels generally representative. Winds, gusts and ground effects simulated.

DATA BASIS

Data employed in this study consist of quantitative pilot ratings, qualitative pilot comments, and time history records of all significant flight parameters. Pilots providing these data were all highly trained, experienced handling qualities evaluation pilots. No single task was performed by less than two pilots, and many were performed by as many as seven pilots. Pilot rating results obtained were evaluated task by task and were interpreted in terms of significant variables of the study and with respect to pilot comments and an evaluation of the time history records. Intuitive and engineering judgments of the effects of pilot background and temperament were made where appropriate.

Pilot Sample

The pilot group consisted of the Bell X-22A test pilots and the MPE-1 Tri-Service evaluation team, which included pilots from each of the three service branches. All of these pilots have flown the X-22A aircraft in hover, made complete transitions in both directions, and evaluated certain selected fixed operating points in the transition flight regime. The individual pilot participation in the various simulators is summarized in Table IX. The overlapping coverage provided by the use of such a broad pilot sample enhances the value of the data correlations by adding an important element of consistency among the various simulations and flights.

TABLE IX. SUMMARY OF PILOT PARTICIPATION

Simulator	Pilot A	B	C	D	E	F	G	H
BLFB	-	-	-	-	-	X	-	X
ALMB	-	X	X	X	X	X	X	X
BHFB	X	-	X	X	-	X	-	X
Flight	X	X	X	X	X	X	X	X

Pilot Rating Data

Since the numerical Cooper pilot rating scale was proposed in Reference 9 as a quantitative means of evaluating handling qualities, many investigators have successfully employed the technique to gain insight and understanding of the man-machine relationships in a wide range of flight and simulator research applications. Areas that have been investigated include criteria for acceptable handling qualities, design requirements for stability and control, and thresholds of pilot sensitivities and tolerances to specific handling qualities dynamic parameters. As a result of broad usage, the Cooper scale has become generally accepted in the handling qualities field. Numerous studies in the literature have used this approach and have established and expressed confidence in the validity of the pilot rating data, in spite of the somewhat subjective aspects of pilot opinions in general. Based on their experience in this line, McRuer et al state in Reference 10 that "In fact skilled pilots (such as the group employed in the present study) can deliver highly selective and reliable relative measures of system behavior" and that "these judgments . . . do not exhibit the extreme variability common to opinion polls." By using such a highly skilled pilot sample, thresholds of pilot sensitivity and tolerance to individual dynamic response parameters that affect the handling qualities of conventional aircraft were defined by Newell in Reference 11. That report confirms that the handling qualities evaluation comments that are given by an expert handling qualities evaluation pilot are directly applicable to all pilots and are not biased by any unusual charactertistics that might be attributed to handling qualities pilots as a group. The report also states the fact that the standard deviation of pilot ratings (for a given pilot task) is near to and often less than 1 pilot rating unit, and uses this measurement as the definition of threshold of pilot sensitivity to individual dynamic response parameters. This line of investigation was extended to helicopters and V/STOL aircraft by Streiff in Reference 12, where the threshold of pilot sensitivity was considered to be 1/2 pilot rating unit based on data presented in Reference 13, which shows that individual pilots correlate with the group average with an average deviation of approximately 1/2 pilot rating.

The use of pilot rating data in this report as a primary source of quantitative handling qualities data is based on these considerations. In deriving the correlations presented between simulators and flight, pilot ratings obtained for any given task were averaged. Only data that could be interpolated to account for variables in the factors in common category were used. Good agreement was generally obtained among pilots for any given task, so that trends of averaged data are considered to be accurate to within 1/2 pilot rating. The variations of pilot rating data among the individual pilots for each task are presented in the compilations of Appendix II.

Acquisition of both pilot ratings and pilot comments was expedited through the use of a comprehensive series of pilot debriefing questionnaires that were developed specifically to evaluate elementary control tasks in hover and transition. A multiple-choice format consisting of five relative-value adjectives for each task was used. An example questionnaire showing the breadth of detail and general format is given in Figure 5. These questionnaires proved to be extremely useful in gathering, organizing, and correlating the data task by task.

Pilot Rating Scale

The pilot rating scale used for these tests was condensed for the convenience of the pilots. The condensation was based on the revised Cooper rating scale which has been published in Reference 14. The actual form used is presented in Table X.

Time History Records

Continuous time histories of significant flight parameters were recorded in conjunction with all flight tasks performed, both in the simulators and in flight. To simplify analyses, record formats, parametric scalings, and paper speeds were standardized. Voice recordings of pilot comments were made. Simultaneous records were synchronized and individual tasks were identified as the records were being made to facilitate the subsequent data correlation and analysis. The validity of the aerodynamic representation in the various simulations is demonstrated by analysis and comparison of static and dynamic simulator results with flight. Details of these analyses are given in Appendix III.

☐ Flight or
☐ Simulation No. ________ ________ °Duct Angle Date ________
Pilot ________ ☐ Calm
Flight Regime ________ ________ Kn Wind ☐ Gusty ± ________ Kn
Control Mode ________ ☐ Turbulent
________ Kn Trim Speed

	On	1/2	Off
SAS	☐	☐	☐
F & T	☐		☐

Task No.* ________ ☐ Hover ________ ☐ F.O.P. ________
Description: ☐ Other ________

Control and Handling Qualities Evaluation		Subjective Ratings					RCR	Additional Comments**
		Excessive	High	Normal	Low	Minimal		
Control Activity For Task	Overall	☐	☐	☐	☐	☐		
	Pitch Axis	☐	☐	☐	☐	☐		
	Roll Axis	☐	☐	☐	☐	☐		
	Yaw Axis	☐	☐	☐	☐	☐		
	Thrust	☐	☐	☐	☐	☐		
Handling Qualities In Steady Flight	Ability to Control Flight Condition	Poor	Inferior	Average	Superior	Excellent		
	Overall F.O.P. Rating	☐	☐	☐	☐	☐		
	Altitude Control Task	☐	☐	☐	☐	☐		
	Heading/Steady Turn	☐	☐	☐	☐	☐		
	Forward Speed/Attitude	☐	☐	☐	☐	☐		
	Rate of Climb	☐	☐	☐	☐	☐		
	Rate of Descent	☐	☐	☐	☐	☐		
Maneuverability		Poor	Inferior	Average	Superior	Excellent		
	Ability to Initiate	☐	☐	☐	☐	☐		
	Ability to Stabilize	☐	☐	☐	☐	☐		
	Ability to Terminate	☐	☐	☐	☐	☐		
	Overall Performance	☐	☐	☐	☐	☐		
Response to Controls		Sluggish	Slow	Normal	Fast	Very Fast		
	Initial Response to Control Input	☐	☐	☐	☐	☐		
		None	Slight	Mild	Obj.	Unaccept.		
	Overshoot Tendency PIO Tendency	☐	☐	☐	☐	☐		

* State Specific task rated (i.e., Translation, Turn, Roll, Steady Sideslip, Climb, Descent, etc.)
** Comment on Effect of SAS

Figure 5. Sample Pilot Debriefing Questionnaire.

TABLE X. REVISED PILOT RATING SCALE *

	RCR
Acceptable/Satisfactory	
Excellent	1
Good	2
Good enough without improvement	3
Acceptable/Unsatisfactory - Mission degraded	
Annoying - improvement requested	4
Mildly objectionable - improvement needed	5
Very objectionable - major improvements needed	6
Unacceptable - Mission performance seriously impaired	
Inadequate for Mission - improvement mandatory	7
Controllable with difficulty - substantial pilot attention required	8
Marginally controllable - maximum available pilot attention required	9
Uncontrollable - Mission impossible	10

* Adapted from CAL Report 153[14].

ANALYSIS AND DISCUSSION OF SIMULATOR DATA CORRELATIONS WITH FLIGHT

In this section averaged pilot rating data are summarized task by task and are compared with flight for each major flight task category. Results in each category are discussed and interpreted with respect to pilot comments and dynamic response time history data.

The broadest data coverage was obtained for the hover task category, where cases to compare with flight are presented for all simulators and most tasks. The next broadest coverage was obtained for the fixed operating point transition task category, where comparisons for longitudinal tasks were made with flight for all simulators. Lateral-directional dynamics at fixed operating points in transition are compared with flight for the fixed-base simulations; they were not compared for the ALMB because of difficulties experienced with its mechanization. For the continuous transition task category, flight results are compared with results from the BHFB simulation because it is the only simulator that can perform continuous transitions at the present time.

Summaries of tasks in each category are based on analysis of the detailed compilations of pilot ratings and comments presented in Appendix II. Summarized data include appropriate corrections for any differences in SAS levels, among cases compared. Results represent the consensus of pilot opinion of simulated characteristics of the basic X-22A as compared to flight. Significant correlations and conclusions based on trends of pilot ratings and comments with other variables and factors evaluated are contained in the discussions of the individual tasks presented and analyzed in the following sections.

HOVER TASK CATEGORY

Pilot ratings and interpretations of pilot comments for the series of hover tasks evaluated in the different simulations are summarized and correlated with flight results in Table XI.

Height Control Task

Compared with flight, overall ratings of the height control task ran approximately 1/2 unit more difficult on the fixed-base simulators and 1/2 unit easier on the moving-base simulators. Although opinion varied among individual pilots, the consensus was that the overall height control task, in hover, translation, and in climb and descent maneuvers, was reasonably representative of the aircraft in all simulators. This observation is substantiated by the evaluation of height response to collective stick inputs presented in Appendix III. A 6-DOF linearized simulation was judged to be the minimum adequate for pilot

TABLE XI. SUMMARY OF PILOT RATINGS AND COMMENTS FOR THE HOVER TASK CATEGORY

Task		Pilot Ratings (RCR)* BLFB (IFR)	ALMB (VFR)	BHFB (IFR)	Flight (VFR)	Interpretation of Pilot Comments and Results
Height Control		4.5	3.4	4.5	4.0	All simulations equally representative of aircraft with good handling qualities. Linearized 6 DOF is minimum adequate simulation for flight training. VFR motion cues become important when handling qualities are poor and the attitude control task demands more of the pilot's attention. SAS level effects are indirect unless system includes height damping.
Attitude Control	Pitch	2.5	3.0	2.9	3.0	All simulators equally representative in pitch and roll for good handling qualities. Good representation of control forces and motions necessary. Representative gust levels add realism without degrading ratings. Visual motion cues more necessary with low attitude damping. ALMB ratings for pitch and roll degrade 3.25 units from 1/2 SAS to NO SAS. No degradation between 1/2 and FULL SAS. BHFB and BLFB uncontrollable with NO SAS. Minimum realistic IFR simulation is 6 DOF linearized with angular motion. IFR yaw displays easy to use but unrealistic. Peripheral vision cues desired for IFR. Yaw rating for FULL SAS degrades by 3/4 to 1 unit with 1/2 SAS and by 2 to 2 and 1/2 units with NO SAS.
	Roll	3.0	3.0	4.0	3.25	
	Yaw	3.0	2.4	3.0	2.5	
Translation Maneuvers	Forward/Aft	3.0	3.0	3.0	3.0	One of the most realistically represented maneuvers. Tasks require careful definition for comparison with flight. Pilots prefer technique of trimming pitch attitude with thrust vector angle rather than pitch stick. Lateral translations more difficult because roll attitude cannot be trimmed. ALMB physical attitude cues realistic. Large untrimmed attitudes in the ALMB degrade ratings by 2 units compared to 3 units in flight. Reductions in SAS more noticeable in lateral translations and more in fixed than moving base. Gust evaluations in the ALMB suggest that translation ratings are degraded by gusts by 1 unit for FULL SAS and 1 and 1/2 to 2 units for 1/2 SAS.
	Lateral	3.0	2.5	3.0	2.6	
Hovering Turn Performance		3.0	2.1	3.0	2.5	One of the most difficult tasks to simulate realistically. Pilots prefer motion and VFR cues. ALMB simulation rated best within angular travel limits. Task easily performed IFR in fixed base also, but not realistic. Improved displays needed for IFR in all simulators.
Hover in Ground Effect		NA**	2.8 Calm 4.5 Gust	NA**	5.6	Ground effects representation unrealistic without motion and gusts. Correlation obtained between ALMB simulation and flight. Degrade simulator results by 3 units for ground effect simulations without gusts and by about 1 unit for simulations with gusts in order to predict flight results.

* Ratings apply to FULL SAS and calm air except where noted.

** NA denotes not applicable.

training. Cockpit motion is also highly preferable, especially when handling qualities are borderline.

Both the BLFB and the BHFB are considered to be equivalent for the height control task on the basis of the pilot ratings and comments received and the comparisons of dynamic response time histories. The fixed-base simulators were considered to be more difficult to fly than the aircraft, because the vertical cues provided were generally inadequate substitutes for the visual motion cues available in flight. Pilots with the most experience in these simulators felt that vertical rate was a prime cue, because it helped them to anticipate height changes, but pilots with less simulator time found it difficult to use. In general, pilots seemed to be able to hover and maintain altitude satisfactorily after a reasonable amount of practice. Performance of the task was imparied by the lack of a hand support for making small adjustments to the collective stick which had a tendency to drop slightly from the set position. These factors probably contributed to some slight degradations in simulator ratings relative to flight, but the effect on the data is believed to be uniform since the same collective stick was used for all simulators.

The fact that the ALMB rated easier than flight is attributed to the unobstructed view from the cockpit that provides even better peripheral-vision cues than are available in the aircraft. Still another factor is an unconscious tendency of the pilot to maintain a tighter control loop in the ALMB than in the aircraft in his efforts to stay well within the confines of the flight cube. In this way, adverse aerodynamic effects that have been included in the simulation are prevented from developing as they do in flight, where the unlimited flight space encourages a more relaxed pilot control loop. Vestibular motion cues were judged to play a relatively minor role in the height control task, because vertical accelerations in hover are ordinarily low and were masked to a large extent by turbulence which was introduced by the gust model. Without gusts, slightly better ratings were obtained.

All simulations were judged to be generally representative of the aircraft, in that steady hover and rates of climb and descent could be readily established and maintained, and there was essentially no attitude coupling with thrust control inputs. As in the aircraft, height control in translation was more difficult than in climb and descent because of vertical and angular acceleration characteristics which accompany translation and which degrade the height control rating by about 1 unit.

With decreasing SAS levels, the height control task remains the same, but the ratings suffer a gradual erosion due to increasing levels of work load and pilot concentration required for attitude control. Reductions from FULL to 1/2 SAS are generally in a range of low pilot sensitivity, where for a wide range the

effect on handling qualities of changes in SAS parameters is very nearly within the threshold of the pilot's ability to detect. Pilot ratings received in this range were only moderately degraded for both fixed- and moving-base simulators. For the height control task, this degradation amounted to approximately 1 unit in the fixed base and 3/4 unit in the moving base. Further decreases in SAS level enter the range of higher pilot sensitivity, where the differences in cues between fixed- and moving-base simulations are much more significant. As the work load increases, the pilot spends more and more time on the attitude control task, so that he tends to withdraw his attention from the height control loop and tolerates increasingly greater variations in altitude. With the visual and motion cues available in the ALMB, several pilots evaluated the condition of NO SAS, giving the height control task an average rating that was degraded 3 units from the FULL SAS condition. In comparison, most pilots were unable to fly the fixed-base simulations with NO SAS, a fact which emphasizes the importance of visual and motion cues at the reduced levels of damping.

Attitude Control Task

The summary of pilot ratings for attitude control in hover that appears in Table XI displays good agreement with flight results. Ratings for all simulators agree with flight results within ±1/2 pilot rating unit, which is ordinarily considered to be within the threshold of pilot sensitivity. Because of the inherently high control powers and sensitivities, attitude response to control was immediate about all axes; most control inputs consisted of very small amplitude control spikes. In general, roll attitude was rated slightly more difficult to control than pitch, particularly in higher steady-wind conditions, where duct rotation could be used to alleviate the pitch attitude but not the roll attitude. In the ALMB and in flight, the procedure of trimming the higher pitch attitudes with duct rotation was actually preferred by all pilots. With the fuselage relatively level, the pilots were better able to judge the effects of control inputs and to avoid the disorientation that occurs when pitch attitude, and hence their own physical orientation, departs excessively from the accustomed norm.

In the aircraft, the yaw axis is rated the best control axis in hover. The rudder pedals are very effective, and yaw control activity in steady hover is minimal. There is a slight tendency to settle in height with yaw control inputs, but there is no other coupling due to yaw control. In the simulators, the yaw axis is also considered to be best. Ratings in the ALMB agreed best with flight, probably because of the better visual cues and the tighter control loop required by the limited flight cube. Ratings in the BLFB and BHFB average approximately 1/2 unit worse than flight. The difference in rating is attributed to persistent difficulties with yaw trim drift, which is a typical complaint for IFR tasks even for in-flight tasks. The fixed-base yaw control ratings were also degraded because of the nature of the yaw display, which was considered to be a poor and

unrealistic presentation. Suggested improvements included the simulation of peripheral-vision yaw rate cues in some form.

The stabilized hover task in the fixed-base simulator was considered to be roughly equivalent to the moving base, despite a different piloting technique that was used. The difference arises from the realistic physical attitude cues developed in a moving-base simulator in steady winds (and/or during translation maneuvers). These cues are generally helpful and increase in importance as damping levels and visual attitude cues diminish. In fixed-base simulators, these physical cues are obtained by continuously scanning the attitude scope presentation. From the ratings and comments received for near-optimum levels of damping, the stabilized hover task is judged to be relatively easy and compares reasonably well with flight, whether performed as a VFR or an IFR simulator task.

With decreasing SAS levels in the aircraft and in all simulators, pilots commented on an increased level of control activity required, but they felt that for the task of steady hover near trim, they could compensate readily for 1/2 SAS levels in the pitch and roll axes without degrading their ratings significantly. On an average, ratings obtained in the ALMB with gust levels judged to be representative of flight showed essentially no degradation in rating for 1/2 SAS; the ratings showed a decrement with NO SAS of approximately 3.25 rating units for pitch and roll control, which degrades the overall pilot rating to 6.0 from the FULL SAS value of 2.6. Ratings of yaw control degraded with reduced levels of SAS by an amount which was approximately the same for all simulations as in flight; from 3/4 to 1 unit for 1/2 SAS, and from 2 to 2-1/2 units for NO SAS.

Results of the moving-base simulation with NO SAS are generally in agreement with X-22A flight experience obtained in and around hover trim, and they contrast sharply with performance in the BLFB and BHFB simulators, which were uncontrollable with NO SAS. As previously mentioned, this disparity in pilot ratings and performance points up the importance of visual and motion cues for flight systems with design values of dynamic parameters in ranges of high pilot sensitivity.

Gust levels evaluated in the ALMB produced essentially linear accelerations and presented no attitude control problem. The higher gust levels evaluated were judged to be much stronger than those ever experienced in flight with FULL SAS. Attitude response to peak gusts was minimal and in agreement with flight results. At 1/2 SAS, gusts were more noticeable but still caused no particular problem. Even with the unrealistically high gust levels, the ALMB simulation could be flown with NO SAS by maintaining a tight control loop. Since aerodynamic coupling terms about the yaw axis in the X-22A are negligible, winds and gusts had no particular influence on the yaw control ratings for any level of SAS.

Translation Tasks

Both forward/aft and lateral translation maneuvers were considered to be the most realistic tasks performed in all simulators, as indicated by the summary of pilot ratings in Table XI. In the aircraft, the task of steady translation is like the attitude control task of hover in a steady head or crosswind, both in pilot technique and flight behavior, except for the visual motion cues that accompany the translation. As performed in the simulators, these tasks were even more alike since visual and vestibular motion cues were available in the ALMB simulator only during transient motion and not in steady state. The ratings given for the translation task include consideration of the initiating and terminating transient response. Forward translations in flight are easy to start and stop. Only small control inputs are required, and aircraft response is immediate. Because of this rapid response, the controls resemble an attitude command system, and there is a tendency to overshoot and PIO without conscious preventive effort. Some collective control with speed change is also required, making an equilibrium speed somewhat difficult to achieve. However, once obtained, an equilibrium speed can be maintained quite well by monitoring attitude. All of these behavior characteristics were represented very well in all simulators. Control positions and forces required to perform and stabilize maneuvers were very much like those required in flight. At the higher forward translation speeds, pilots preferred to trim the higher nose-down pitch attitudes with duct rotation, either to maintain a more comfortable attitude, as in the ALMB and in flight, or to keep the horizon trace centered on the scope presentations, as in the BLFB and BHFB. Very high pitch attitudes were degraded relative to the level fuselage condition by approximately 2 pilot rating units, with nose-up attitudes being rated slightly easier to stabilize than nose-down.

Lateral translations in the aircraft were also considered to be an easy task but more difficult to stabilize than in the forward direction, because the concept does not provide for roll attitude trim. This effect is particularly noticeable at lateral speeds above 15 knots, where the roll angles developed start to feel large and uncomfortable. In this respect, the ALMB simulation and its physical attitude cues is most representative of flight. The degradation in pilot ratings at the higher bank angles amounts to approximately 2 units in the ALMB, as compared to 3 units in flight. A lack of capability for lateral stick trim in the ALMB was considered to be annoying, but it was generally compensated for by the pilots without significantly affecting the ratings. In making lateral translations, particularly in the BLFB and BHFB, the pilots felt that roll attitude was more difficult to monitor than lateral speed. In all simulators, as in flight, lateral translation maneuvers were easy to start and stop. Representation of control response was very good, and, as in the aircraft, restraint was required to avoid a noticeable tendency to overshoot and PIO, a tendency which became objectionable at reduced levels of SAS. A reduction from FULL to 1/2 SAS

seemed to have a more pronounced effect on the ratings for lateral translations than for forward translations, and produced a gap between the fixed-base results and the moving-base and flight results that continued to widen with further decreases to NO SAS. In the ALMB and in flight, ratings for levels between FULL and 1/2 SAS held approximately constant for forward translations and degraded by about 1/2 unit for lateral translations. These results compare to no degradation for forward translations and a degradation of 3/4 unit for lateral translation in the BLFB and BHFB. Further reductions to NO SAS gave degradations of approximately 3 units from the FULL SAS values for the moving-base simulator, as compared to uncontrollable ratings for the fixed-base simulator.

An evaluation of the effects of gusts in the ALMB indicated that, in typically gusty air, ratings of the translation tasks degraded by about 1 rating unit at FULL SAS and by 1-1/2 to 2 units for 1/2 SAS.

Hovering Turn Task

Hovering turns, which in flight are among the easiest tasks, are among the most difficult to simulate realistically because of the large range of motion and peripheral-vision cues required. In flight, the aircraft can make 360° turns with ease, and the pilot can stop and hold heading at any point in turn. In winds, duct rotation is usually coordinated with pitch and roll control to help limit drift without developing excessive pitch attitudes.

The ALMB simulation was the most realistic, but heading excursions were limited to ±40°. Yaw maneuvers and heading changes in this range were rated very similar to those performed in the aircraft. In performing the task, the pilots used visual cues exclusively; these were judged to be better than the visual cues in the aircraft because of the proximity of the walls and the unobstructed view from the simulator cockpit. As in the aircraft, small pedal inputs produced a steady-rate turn, whereas larger inputs seemed to produce an accelerated turn. These characteristics are explained in Appendix III.

With reduced levels of SAS, pilot work load increased because the pilot had to enter the loop earlier to prevent his heading from drifting. Effects of gusts were more noticeable with 1/2 SAS. Slight tendencies to overshoot and PIO were also more noticeable with 1/2 SAS, and pilot ratings were degraded by approximately 1 unit from FULL SAS. With NO SAS, the work load increased further, and the FULL SAS rating was degraded by 2 to 2-1/2 units.

In both the BLFB and the BHFB the simulated aerodynamic and control response characteristics were the same but without peripheral-vision cues. The heading trace went off the scope at about ±30°, and additional heading information was provided by a second instrument which indicated a range of ±180° for making

larger turns. With these instruments, pilots were able to change heading easily and rapidly, but they felt that the displays were not adequately representative of the true flight cues. The simulator also exhibited a persistent drift in yaw trim, which is known to be typical even of in-flight IFR tasks. However, the drift annoyed the pilots and contributed to the unreal impressions of the displays.

The pilot ratings in Table XI for hovering turn performance in the various simulators were generally good, reflecting more the relative ease of the simulator task than its realism compared to flight. Since the flight task is also easy, the ratings compare well, but for this task all simulators are considered to be limited. The ALMB is rated best for VFR simulation of turns within its limited angular travel. For IFR simulations, all simulators need improved displays.

Hover Task in Ground Effect

Results of a series of flights in the ALMB which evaluated the hover control characteristics in simulated ground effect, as compared to flight, are summarized in Table XI. Ground effects simulated include thrust, pitching moment, rolling moment, and yaw control moment dependencies. The summary of pilot ratings represents an average of the broad pilot sample used both in the ALMB simulation and in flight.

Ground effect in the aircraft is characterized by a high level of turbulence, which produces random forward and lateral accelerations, and by a strong ground cushion with a region of reduced or possibly negative ground effect slightly above. With these height characteristics, the aircraft tends to hang suspended a few feet above the ground and requires definite collective inputs in order to ascend and descend through ground effect. The cushion characteristic as simulated was considered to be fairly representative of flight, but it occurred at a lower altitude and did not seem to be as strong. Pilot judgments were made by performing hands-off vertical oscillations and general hover maneuvers on the cushion, as was done in flight. Attitude control techniques and rating trends were similar to those obtained out of ground effect (OGE). Ratings of ground effect without turbulence ran significantly better than flight, and the simulation was considered to be definitely not representative. The turbulence level in ground effect (IGE) was simulated with a random gust model which was evaluated for several gust levels. The lowest gust level tested provided the best representation when introduced in the x and y inertial directions.

The incorporation of appropriate levels of turbulence greatly enhanced the realism of the overall ground effect simulations. Ratings for hover with turbulence IGE degraded approximately 1.7 units, which is much closer to the flight

result but still better by about 1 unit. Since this result is based on a large pilot sample and the ratings are consistent, the correlation shows that a degradation of 1 pilot rating unit should be applied to moving-base simulator ratings of hover IGE when appropriate levels of turbulence are used. Pilot rating results of simulations without turbulence should be degraded by 3 pilot rating units to account for ground effects.

Effects of Motion on the IFR Hover Task

The effects of motion cues on the realism of IFR hover simulations were explored briefly and qualitatively in the ALMB simulator. Piloting tasks were similar to those used for the BLFB and BHFB hover tasks. The lower oscilloscope displayed horizontal position with respect to the boundaries of the flight cube as well as ground velocity. A range of reduced linear motion scaling from fixed base to true motions was explored. In fixed-base operation, pilot reactions were slower than in flight because of a general lack of anticipatory cues. Angular motion alone was a significant improvement. Hence, when linear motion scaling was evaluated, angular motion scaling was maintained in the ratio of 1:1. Although the amount of data obtained was limited by a lack of time, several interesting results were obtained, and the investigation represents an initial effort to sort out the significant factors related to fixed- and moving-base IFR simulation.

With FULL SAS and a 10:1 linear motion scaling, which effectively increases the size of the flight cube, control activity in hover was rated high to excessive, and on a par with BLFB and BHFB results previously obtained. No particular difficulty was experienced with the various hover flight tasks and gust levels evaluated. Although linear accelerations were generally too low to be felt, physical attitude cues were evident and were considered to be definitely helpful. Even with this scaling, the work load in first attempts was high, and occasional linear excursions covered most of the flight cube. However, both pilot performance and ratings improved with practice. With increasingly realistic ratios of motion scaling (i.e., scaling → 1:1), the hover tasks became progressively more difficult because larger attitude changes and faster judgments and control motions were required just to stay inside the smaller flight cube; once a large control displacement was required, it was very hard to regain control.

It was found that the level of pilot learning played an important role in evaluating which linear motion scaling in IFR is most representative of VFR operation. Most pilots were introduced first to the 1:1 ratio of linear motion scaling, and ratings of the hover work load ranged from extremely difficult to intolerable for the size of the flight cube. However, further flight experience with a progressive series of scaling ratios ranging from 10:1 back down to 1:1 resulted in an improved hovering capability and upgraded pilot opinions. Height

control was a slight problem under IFR conditions, but typical gust levels could be managed quite well. A 3:1 linear scaling was considered to be approximately as difficult as, and equivalent in work load to, the VFR task with FULL SAS (although in this scale, stabilized hover was difficult with 1/2 SAS and uncontrollable with NO SAS). Nevertheless, with FULL SAS, ground position and height control were not particularly troublesome; as in flight, the yaw axis was considered to be the easiest to control.

Whereas the BLFB and BHFB could not be controlled in hover with NO SAS, it was found that, at a motion scaling ratio of 10:1, the ALMB could, although the work load remained high throughout the flight task. Because the linear accelerations were essentially imperceptible in this scale, the capability to hover with NO SAS is attributed to the presence of the pitch and roll attitude cues, which aided the pilot in interpreting the cockpit information displays and anticipating the control motions required. This result has significance because it demonstrates that a ground-based simulator, which provides flight cues through a combination of angular motion and visual instruments, can be flown even in situations of high pilot sensitivity and should be sufficiently representative of flight to permit the evaluation of many IFR hover tasks.

Hover Dynamics

A summary of pilot ratings and comments for dynamic evaluations of the individual control axes in hover is given in Table XII, as condensed from the more complete data compilations presented in Appendix II. Ratings and comments represent opinions of general handling characteristics in and around hover and of a series of carefully performed step- and pulse-type control inputs for each control axis. Static stability and dynamic response time history records of significant flight parameters in each control axis for the different simulations are analyzed and compared with flight results in Appendix III. Based on the qualitative comparisons of Table XII and the quantitative comparisons of Appendix III, the simulated dynamic characteristics in hover are judged to be in substantial agreement with flight. The dynamic characteristics in each control axis are discussed in the following sections.

Height Dynamics

Response to thrust control in the ALMB was judged to be good, with a height response time lag approximately the same as in the aircraft. Fixed-base simulator results were also considered to be representative of flight. Neither the simulators nor the aircraft exhibits any noticeable height damping, and there are no significant couplings due to thrust control. In the aircraft, a vertical oscillation can be developed IGE. This characteristic was simulated in the ALMB but was not noticeable. In the ALMB,

TABLE XII. SUMMARY OF PILOT RATINGS AND COMMENTS FOR DYNAMIC FLIGHT TASKS IN HOVER

Axis	BLFB and BHFB	ALMB	Flight
Height Dynamics	Slow thrust response. Representative.	Good response. Similar to flight; time lag approximately as in aircraft (RCR 3). With ZERO SAS and calm (RCR 5); with ZERO SAS and gusty (RCR 7-8). Cues similar to flight. No noticeable height damping. No control coupling. Collective sensitivity estimated at 0.5 g/in.	Slow thrust response. Minimum physical vertical acceleration cues most noticeable in descent. Engine transients barely audible. No bothersome control coupling noted. Ground effect oscillation between 5 and 10 ft. undesirable (RCR 5).
Pitch Dynamics	Control response essentially deadbeat to pitch inputs.	No problem longitudinally. Pulse inputs felt more representative than pull and holds. Size of flight cube limits maneuvers. Pitch damping evident. Input results in attitude which holds as speed builds.	Quite stable in pitch and roll. Feels like very fast response attitude control system (RCR 3) with high frequency and low damping. No overshoot (RCR 2) but aircraft feels like it might PIO if moved too fast. Coupled pitch attitude-speed-height motion with pitch input. Period is approximately 8 sec; damping neutral. Much faster response with 1/2 SAS.
Roll Dynamics	Essentially deadbeat response to aileron pulses.	Initial response is similar to flight. Lateral translation limits prevented evaluation of height coupling due to roll. Bank angle proportional to stick position. Roll damping appeared less than pitch but not degrading.	Fast roll attitude response to push and hold input. Attitude decreases as speed builds up. Height loss noted with speed. No yaw due to lateral velocity. Response noticeably faster with 1/2 SAS.
Yaw Dynamics	Essentially deadbeat response to rudder pulses.	Rudder response excellent. Identical to flight. Order of magnitude better than BHFB for yaw control. Attributed to better cues.	Yaw rate response to small yaw steps. Control sensitivity and damping satisfactory (RCR 2). Larger step gives acceleration response (RCR 4). Mild loss of height noted. Response noticeably faster with 1/2 SAS (RCR 5).

degradations in pilot ratings of height control dynamics were obtained for the effects of SAS and with gust level representative of flight. Degraded ratings at reduced SAS levels were actually the result of increased pilot concentration on attitude control, since the height parameters themselves are unaffected by changes in SAS. These degradations amounted to 2 units for a reduction from FULL to NO SAS without gusts and a further degradation of 2-1/2 units for NO SAS with gusts. From the consensus of pilot ratings and the comparison of time history records of height dynamics, Figure 14, the dynamic height response characteristics as represented in all simulators are judged to be equivalent to the aircraft in hovering flight.

Pitch Dynamics

Response to pitch control in and around hover was well represented and in agreement with flight in all simulations. With FULL SAS, the aircraft feels quite stable in hover and responds very quickly to pitch control inputs. The response feels like an attitude control system, and, although there is no overshoot, the aircraft feels like it might PIO if the controls are moved too fast. The longer term response to pitch control inputs is a coupled oscillatory motion involving attitude, height, and speed, with essentially neutral damping and approximately an 8-second period. Responses with 1/2 SAS are noticeably faster. Pitch dynamics in the aircraft with FULL SAS are rated RCR 2-1/2. In the ALMB, the response to pulse-type inputs was considered more representative than pull-and-hold-type pitch inputs, which were harder to evaluate because the size of the flight cube limited the duration of the maneuvers that could be performed.

Dynamic response time histories, of both pulse-type and pull-and-hold-type pitch inputs in the different simulators and in flight, are compared in Figures 15 and 16 in Appendix III. Responses of important parameters were similar to flight in all simulators; these results confirm the pilot judgments that the representation of pitch dynamics in hover is generally equivalent to flight.

Roll Dynamics

In the simulators as in the aircraft, roll and pitch dynamics in hover are similar. The response to roll inputs in and around hover is very fast. The immediate response to a lateral stick input is a roll attitude. This characteristic was well simulated in fixed- and moving-base simulators. A speed-height-attitude coupled motion developed over the longer term as in the pitch axis. This motion could not be fully evaluated in the ALMB because of the limits of the flight cube. There was no apparent yawing motion due to lateral speed. Response with 1/2 SAS was noticeably faster.

Dynamic response time history records of pulse- and step-type roll inputs for the different simulators are compared with flight in Figures 17 and 18 and are discussed in Appendix III. Results indicate that roll dynamics in hover were well represented.

Yaw Dynamics

In the aircraft, with FULL SAS, yaw control sensitivity and damping are rated satisfactory. Response to small inputs is a yaw rate (RCR 2), and response to large steps is an acceleration response (RCR 4). There is a mild but noticeable loss of height with yaw control. Responses with 1/2 SAS are noticeable faster. In the ALMB simulation, the yaw control response characteristics were judged to be identical with flight and much better than the representation in either the BHFB or the BLFB simulations, which were both downrated primarily because of their yaw information displays. Another contributing factor was the FULL SAS value of yaw damping in the BHFB, which was approximately 1/2 of the value representative of flight. A lack of limits on SAS authority in the BLFB affected only large control inputs in the yaw axis.

Dynamic time history records of responses to rudder pedal inputs in hover in the different simulators and in flight are compared in Figure 19 and are discussed in Appendix III. Results generally substantiate the observations of the pilots.

FIXED OPERATING POINT TRANSITION TASK CATEGORY

For flight tasks in this category, all simulators were operated IFR, as compared to VFR operation in flight. Because the IFR simulator tasks were not directly comparable to VFR flight tasks, pilots were reluctant to give numerical ratings. Therefore, results obtained are more qualitative than in hover. Tasks in this category are discussed under two subcategories: (1) steady flight tasks, which include longitudinal static stability and trim, directional static stability and dihedral effect, and banked turns, and (2) dynamic flight tasks, which include the longitudinal long- and short-period modes and responses to pitch controls, and the lateral-directional dynamic mode and responses to roll and yaw controls.

Steady Flight Task Category

Pilot ratings and comments received for tasks in the steady flight category indicate that the aircraft characteristics, in general, were adequately represented in terms of control forces and motions needed to achieve equivalent steady flight conditions. A lack of pilot experience in the IFR simulators was found

to have an effect on both performance and ratings, particularly in evaluating regions of low static stability. The yaw displays were considered to be poor and inadequate substitutes for the VFR cues that are available in flight. Turn characteristics generally were well represented in all simulators. Turn initiation compared well with flight, and control forces and motions were judged to be comparable. The fact that all simulators were judged to be approximately equivalent for IFR flight operation implies that a linearized 6-DOF fixed-base simulator is sufficient for pilot familiarization and evaluation of handling characteristics at steady flight conditions in fixed operating point transition. The individual tasks in the steady flight category are discussed in more detail in the following sections.

Longitudinal Stick Position Stability and Trim

The longitudinal flight characteristics of the aircraft at fixed operating points in transition are dependent to some extent on the thrust control mode of operation. Stick position stability characteristics vary over the duct angle range, but in the collective mode at duct angles below about 60° they are neutral to slightly negative. Pilots consider the aircraft to be generally easy to fly but difficult to trim at a precise speed, attitude, or altitude. Pilot opinions of these characteristics varied widely in flight, from RCR 2.5 to RCR 5.0 for VFR operation, the average being RCR 3.75. Although considered to be satisfactory for a VSS research aircraft, these characteristics were rated unacceptable for IFR operation, and pilot ratings received for IFR were degraded by approximately 2 rating units, to RCR 6.0.

In the simulators the stability and trim characteristics were actually very well represented, as shown by comparisons of trim stick position versus speed and hands-off time history records for all simulators with flight presented in Figures 11 and 20. In the BHFB, pilots with little or no experience in the aircraft found stability and trim difficult to evaluate, and, although they had trouble trimming, their comments indicate that they could not distinguish the true stick-position stability level. The BLFB and the ALMB were evaluated by pilots with more experience, both with the aircraft and with IFR fixed-base simulators. Although this pilot sample is quite limited, both the comments and the ratings received agree well with flight results. These results illustrate the importance of providing pilots with sufficient learning time in the simulator to familiarize themselves with substitute flight cues, to practice coordinated control motions, and to develop a proficient perceptive and reflexive capability, as a basis for simulator evaluations.

Static Directional Stability

Pilot ratings of static directional stability were obtained by observing the results of rudder inputs and by the performance of steady sideslips. At all fixed operating point transition flight conditions evaluated, the aircraft exhibits relatively strong stability (right pedal for nose right) beyond side-slip angles of $\pm 2^\circ$ and positive dihedral effect (left sideslip produces right roll). In the range of sideslip between $\pm 2^\circ$, a reduced level of directional stability is evident.

The simulators were judged to be representative with respect to control forces and motions for comparable maneuvers. They also exhibited positive directional stability as in flight. However, the yaw displays were considered to be poor and inadequate in all simulators, and the BLFB and ALMB were limited in sideslip capability by equipment difficulties related to the computer and displays. Because of these problems, it was not possible to establish a good correlation of pilot ratings for this task. Nevertheless, the comparisons of pedal position versus sideslip angle and bank angle indicate that directional stability was adequately simulated in the BHFB and BLFB for flight conditions in and around trim.

Banked Turns

The turn characteristics of the aircraft were extensively evaluated through the transition range. In general, a greater pilot effort is required to co-ordinate turns than for most conventional aircraft. An initial adverse yaw develops if the turn is initiated with the lateral stick only, but smooth turn entries can be made by leading the lateral control with the rudder. Pilot ratings obtained in flight averaged RCR 3.7.

Pilot comments and ratings of the different simulators indicate that turn characteristics were generally well represented. In the BLFB, the response to turn initiation was rated normal to fast, and turn entry compared well with flight. Control forces and motions were also judged to be comparable. Turns with bank angles above 20° were more difficult than flight because of a restriction caused by equipment scaling, which was not corrected for lack of time. In the BHFB, turn entry was also judged to be comparable, but rudder motion required to coordinate the turn seemed low compared with flights. In the ALMB, the task was performed IFR, and the response to control motions was also judged to be approximately as in flight.

Dynamic Flight Task Category

Pilot comments received for tasks in the dynamic flight category also indicate that the aircraft was well represented in all simulations, and numerical ratings for these tasks were more freely given. A summary of the pilot ratings and comments for the dynamic flight tasks at fixed operating points in transition is included in Table XIII. More complete compilations are presented in Appendix II. Pilot comments for the dynamic motions are reasonably consistent among simulators, and pilot ratings for all agree with flight within ±1 rating unit for all of the standard dynamic flight tasks.

The lateral-directional mode can be excited by several test techniques, including walking the rudder and release from a steady sideslip. The best test technique appears to be a cross-coupled lateral-directional spike. Lateral-directional comparative results for the ALMB in transition were not obtained because of difficulties involved with the simulation setup and a lack of sufficient time. However, the reasonable agreement obtained with the other simulators in the longitudinal mode implies that similar results can be obtained with the ALMB in the lateral-directional mode.

The agreement of simulator dynamic behavior with flight is also indicated by comparisons of time histories of important flight parameters in Appendix III. Results imply that the representation of the aircraft dynamic characteristics in any of these simulators is adequate for flight evaluation and test pilot training purposes.

CONTINUOUS TRANSITION TASK CATEGORY

The flight regime between vertical and conventional flight is spanned by a pilot-controlled procedure that converts the aircraft in flight from one aerodynamic configuration to another. Because of the continuously variable aerodynamics and the rapidity with which the operation can be performed, aircraft flight behavior in continuous transitions is more time and speed dependent that at fixed operating points in transition. Compilations of pilot ratings and comments for conversion and reconversion maneuvers performed by a broad pilot sample in the BHFB simulator and in flight are given in Appendix II.

In general, the BHFB simulation represents the important characteristics of transition flight behavior. Pilot control techniques for conversions and reconversions, which were developed in the simulator prior to flight in the aircraft, were substantiated by actual flight experience. Pilot ratings of the simulated transition task averaged RCR 5 overall, which is a degradation of approximately 1-1/2 units from flight (RCR 3 and 1/2). The difference in ratings is attributed to the combined effect of the lack of realistic visual, aural, and vestibular

TABLE XIII. SUMMARY OF PILOT RATINGS AND COMMENTS FOR DYNAMIC FLIGHT TASKS AT FIXED OPERATING POINTS IN TRANSITION

Task	Duct Angle	Pilot Ratings				Summary of Pilot Comments
		BLFB	ALMB	BHFB	Flight	
Longitudinal Long-Period Dynamic Mode	60°	3	NR	NR	2	Nonoscillatory neutral with hands off in trim.
	30°	4	5	5	4	Nonoscillatory and slowly divergent. Faster out of trim.
	0°	4	NR	5	4.5	Nonoscillatory and slowly divergent.
Longitudinal Short-Period Dynamic Mode	60°	NR	NR	NR	2.5	Nonoscillatory, heavily damped, and fast-responding to pitch inputs at all duct angles.
	30°	3	3	4	2.5	Essentially dead beat. One pilot felt somewhat uncomfortable with these characteristics, but not enough to degrade ratings.
	0°	NR	NR	3	2.5	
Lateral-Directional Dynamic Mode	60°	3	NR	NR	4	Motion is generally a damped oscillation with a period of 5 to 8 seconds. Roll motion predominates in mid-transition, and lateral oscillations tend to persist. Modes are least coupled at 0° duct angle.
	30°	3	NR	NR	4	
	0°	3	NR	NR	4	

NOTE: NR denotes not rated.

motion cues in the simulator. The correlation is considered to be generally valid for projecting pilot ratings of continuous transitions in flight from results obtained in fixed-base simulators for aircraft with handling qualities and aerodynamic characteristics similar to the X-22A.

Although the correlation is significant in itself, the real value of the BHFB simulator lies in its ability to explore continuous conversions and reconversions to identify problem areas, and to establish piloting techniques and operating procedures throughout the transition regime. An evaluation and analysis of the correlated pilot comments showed that essentially the same difficulties were encountered and that the same piloting techniques were required in the simulator as in flight, for both conversion and reconversion maneuvers.

Typical level-flight conversion and reconversion maneuvers are performed using the following technique. Conversion is initiated by rotating the ducts forward intermittently, using the collective stick primarily as a height control and the pitch stick as a speed/attitude control. As forward speed builds, a forward pitch control motion is required to keep the fuselage level. With continually increasing speed through midtransition, the collective stick is reduced to prevent climb. In the final stages of conversion (i.e., the duct angle range from 30° to 0°), there is a marked change in pitch trim which requires a steady and substantial aft stick motion to hold up the nose, and an increasing collective stick motion is required to maintain altitude. For climbing conversions, a higher level of collective stick and pitch attitude is maintained through midtransition. Reconversions are initiated by a slow, intermittent duct rotation over the region of large trim change from duct angles of 0° to about 30°. Reduced collective and forward pitch control motions are used in combination to control a relatively strong climb tendency associated with duct rotation. This tendency is relieved through midtransition, and further reductions in speed and the approach to hover require a nose-up pitch control motion and a strong increase in collective stick in order to keep the fuselage level and to maintain altitude.

In the BHFB, the lack of realistic visual motion cues, and the inability of the altitude and vertical rate displays to provide adequate substitutes, made the collective control task to hold altitude in reconversions seem harder to manage than in flight. Increased realism in this area might be achieved by a visual representation of real-world peripheral cues, as might be provided by a TV monitor, possibly but not necessarily coupled with angular motion cues. One pilot commented that roll control in the simulator required considerable effort and rated it sensitive with too little damping. This judgment might be expected in view of the lower SAS levels present in the simulator, as compared with flight, and may be partially responsible for the adverse correlation.

In other respects, pilot opinions of the simulator and flight characteristics were essentially the same. In flight as in the BHFB, level conversions were rated approximately 1 rating unit easier to perform than level reconversions. Trim and attitude changes in the simulator were judged to be reasonably representative of flight. Speed response to duct rotation was good at both ends of the speed range, making transition in either direction easy to start and stop. On the average, control responses through transition were rated normal. In flight, the work load was rated average for level conversions and high for reconversions.

Transitions in the BHFB and in flight were made using both rapid (continuous) and slow (intermittent) thrust rotation techniques. The rapid transition technique was preferred because, by holding the fuselage level and controlling altitude with the collective stick, the acceleration or deceleration characteristics produced by a rapid duct rotation rate carry the aircraft smoothly through the center of the transition envelope with a minimum of pilot effort required to monitor the combination of speed and duct angle. The rapid technique was rated better by about 1-1/2 rating units. In slow conversions in flight, a tendency toward lateral PIO was noted which was not apparent in the more rapid operations. This effect is apparently due to the additional time spent in the regions of low roll-yaw dynamic stability during the slow transitions.

In analyzing the data, it was evident that the ratings improved with the level of pilot learning. Most of the pilots had insufficient time in the simulator and in the aircraft to thoroughly familiarize themselves with the flight characteristics, but they tended to give increasingly better ratings in both the simulator and in flight as their proficiency improved with increased flight experience. Many of the observations and comments made by the military pilots are generally recognized but automatically compensated for by pilots more familiar with the simulator and the aircraft.

SIMULATOR CAPABILITIES AND LIMITATIONS

Relative capabilities and limitations of the simulators to represent flight for specific tasks in hover and transition are established by the analyses and comparisons of the study. These results are summarized in Table XIV. The minimum simulator judged to be sufficiently representative of flight for most engineering purposes is designated "M" in the table for "minimum adequate." More complex simulators that provided a further degree of fidelity are designated "S" for "satisfactory." In general, the moving-base simulator was most representative of flight and is therefore designated "B" for "best" simulation. The pilot rating correlations developed in the preceding section for the various tasks and simulators form a basis for projecting flight characteristics from results obtained with these ground-based simulator types.

The Bell fixed-base simulator mechanized with 6-DOF linearized equations of motion for flight at specific operating points (e.g., hover) produced dynamic response characteristics that were comparable to flight. Deficiencies in simulated VFR flight were related to the lack of representative visual motion cues; however, important handling qualities characteristics were readily evident to trained test pilots. This simulator is therefore considered to be the minimum adequate simulator for most fixed operating point flight tasks in hover and transition. This type of simulator is useful for evaluating specific problems in the areas of stability and control, and flight control systems, during the design and development phases of V/STOL aircraft, and for preliminary pilot training.

The Bell hybrid fixed-base simulator mechanized with 6-DOF nonlinearized equations of motion provided the substantially increased capability of continuously variable flight and control characteristics over the complete flight envelope. Dynamic response characteristics to pilot inputs were well represented at fixed operating points as well as in continuous transitions. This simulator was subject to the same lack of representative visual motion cues; however, important stability characteristics, power effects, and control manipulations required in making continuous transitions were representative and readily apparent from the cues provided. This simulator is therefore considered to be the minimum adequate simulator for continuous transition tasks. It is useful for evaluating extreme excursions as well as small perturbations at fixed operating points, for exploring the transition flight envelope fully for unexpected problems, for developing piloting techniques and procedures for continuous transitions, and for preliminary pilot training.

The Ames moving-base simulator mechanized with 6-DOF linearized equations of motion at specific operating points produced dynamic characteristics, and vestibular and visual motion cues in response to pilot inputs, that were comparable to flight. The motion provided eliminated most deficiencies present in

TABLE XIV. RELATIVE CAPABILITIES OF X-22A SIMULATORS			
	Simulator Complexity		
Flight Tasks	BLFB 6 DOF	BHFB 6 DOF	ALMB 6 DOF
HOVER			
Height Control	M	S	B^1
Attitude Control	M	S	B^1
Fwd/Aft Translations	M	S	B^1
Lateral Translations	M	S	B^1
Turns	U	U	S
Takeoff, Landing (IGE)	U	U	M
TRANSITION			
Fixed Operating Point	M	S	S
Continuous Conversions and Reconversions	U^2	M	U^2

B Best

S Satisfactory

M Minimum adequate simulator for preliminary pilot training

U Unsatisfactory

NOTES:

1. 3-DOF angular motion provides much of the improvement realized.
2. Rated U only for aircraft with highly complex transition aerodynamics.

the fixed-base simulator, especially in hover where the tasks performed were considered to be most realistic. Most of this improvement was provided by the 3 degrees of angular motion; however, adequate representation of the vertical takeoff and landing tasks required linear motion as well. The moving-base simulator is considered to be the minimum adequate simulation for vertical takeoff and landing in ground effect. At fixed operating points in transition, peripheral-vision cues provided are incongruous with the equilibrium speed and are therefore unrealistic. Representative peripheral-vision cues for transition have yet to be developed. At present this simulator does not have the capability to make continuous transitions. It is useful for all types of evaluations in hover, and particularly for developing flight techniques for takeoff and landing, for evaluating ground effects, and for advanced pilot training in hover.

CONCLUSIONS

Three different types of ground-based simulations of the X-22A are compared with flight. Comparisons are made in terms of pilot ratings, pilot comments, and time history data of specific flight tasks in hover and transition. Significant conclusions are presented below.

1. Hover flight tasks were rated approximately equivalent to flight in all three 6-DOF simulators. An exception occurred in the moving-base simulator at translational speeds above 15 knots when equilibrium was obtained by large pitch or roll attitudes. Pilot ratings of that task were approximately 1 RCR better than flight.

2. Typical gust levels were evaluated only in the moving-base simulator. Pilot ratings in steady hover in this simulator compared well with flight. In translational maneuvers, gusts degraded pilot ratings with respect to flight, particularly for low levels of damping. This effect is believed to be related to limitations in the size of the flight cube.

3. Motion cues in hover were found to be increasingly important to simulator realism as damping levels were reduced and handling qualities degraded.

4. The only adequate representation of hover in ground effect was provided in the moving-base simulator by using a gust model to represent realistic levels of ground effect turbulence in conjunction with the representation of ground-induced aerodynamic effects.

5. The yaw axis was found to be the most difficult axis to simulate realistically. The 6-DOF moving-base simulator was most representative of flight. In the fixed-base simulator, and in the moving base when flown IFR, cues provided by the yaw parameter displays were unrealistic for both steady hover and hovering turns. Therefore, ratings obtained for these tasks were not related to flight. Efforts to improve yaw parameter displays are recommended and should be directed toward providing better indications of angular rate, preferably in the form of peripheral-vision cues.

6. Initial investigations of IFR hover tasks in the moving-base simulator indicate that compared to fixed base, angular motion cues alone produce a significant improvement in realism and permit evaluations of IFR handling qualities tasks including hover with NO SAS. Linear motion cues have a secondary effect for most IFR hover tasks.

7. The fidelity of simulation of control characteristics and aircraft dynamic response in transition was judged to be adequate and representative of flight in all simulators. The degree of difficulty in performing flight tasks in transition can be related to flight in terms of pilot ratings. A linearized 6-DOF fixed-base simulation is considered to be adequate for test pilot familiarization with both steady-state and transient flight conditions at fixed operating points in transition.

8. The value of the fixed-base hybrid simulation lies in its abilities to explore continuous conversions and reconversions, to identify problem areas, and to establish piloting techniques and operating procedures throughout the transition flight envelope. The simulator represents the important characteristics of transition flight behavior. The addition of 3-DOF angular motion capability to this simulator would provide a significant increase in the degree of realism of continuous transitions, and is recommended.

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APPENDIX I
SIMULATOR DETAILS, EQUATIONS OF MOTION, AND MECHANIZATION

This appendix presents the equations of motion and mechanization limitations for the BLFB, BHFB, and ALMB simulations.

BELL LINEARIZED FIXED-BASE SIMULATION (BLFB)

The cockpit flight controls and instrument panel used for the BLFB simulator are the same as for the BHFB. Hence, both simulations have essentially the same physical limitations, which are discussed in the next section.

Mathematically the BLFB is considerably more limited than the BHFB, as indicated by the complexity of the equations. Aerodynamic stability and control derivatives for the BLFB were linearized for hover and several selected fixed operating point flight conditions in equilibrium transition. This type of simulation does not provide for continuous conversions and reconversions, and the extreme ranges of the X-22A flight envelope where the linearization does not apply cannot be evaluated. Therefore, flight tasks must be designed so that excursions from the flight condition stay within the linearized range of the aerodynamic derivatives. This type of simulation does permit flight evaluations of aircraft handling characteristics (aircraft attitude control coupling, static and dynamic stability, etc.) in and around the fixed operating point for which the derivatives were evaluated. Other mathematical assumptions of the BLFB include small-angle approximations, and ground axis velocities assumed the same as in body axes.

Equations of Motion (Body Axes)

$$\ddot{X} = -g\,\theta - w_o q + (X_o + X_u u + X_w w + T\cos\lambda)/m \tag{1}$$

$$\ddot{Y} = g\,\phi - U_o r + w_o p + (Y_p p + Y_r r + Y_v v)/m \tag{2}$$

$$\ddot{Z} = U_o q + (z_o + Z_u |u| + Z_w w + Z_v |v| - T\sin\lambda)/m \tag{3}$$

$$\dot{p} = \Big[I_{xz}\dot{r} + L_v v + (L_{p_{Aero}} + L_{p_{SAS}})\,p + L_r r + L_{\delta rs}\,\delta_{rs} + L_{\delta rp}\,\delta_{rp} + L_{\delta rp_u}\,\delta_{rp^u}\Big]/I_x \tag{4}$$

$$\dot{q} = \Big[M_u u + M_w w + (M_{q_{Aero}} + M_{q_{SAS}})q + M_{\delta ps}\,\delta_{ps}\Big]/I_y \tag{5}$$

$$\dot{r} = \Big[I_{xz}\dot{p} + N_v v + N_p p + \left(N_{r_{Aero}} + N_{r_{SAS}} \right) r$$

$$+ N_{\delta_{rs}} \delta_{rs} + N_{\delta_{rs_u}} \delta_{rs} u + N_{\delta_{rp}} \delta_{rp} \Big] / I_z \quad (6)$$

Flight Parameters

$$T = T_\beta (\beta_c - \beta_{T=0}); \; T = 0 \text{ for } \beta_c \leq \beta_{T=0} \quad (7)$$

$$\dot{h} = U\theta - w \quad (8)$$

$$\dot{\phi} = p - \dot{\psi} \sin\theta \quad (9)$$

$$\dot{\theta} = q \cos\phi - r \sin\phi \quad (10)$$

$$\dot{\psi} = (q \sin\phi + r \cos\phi) \sec\theta \quad (11)$$

$$\sin\phi = \phi \quad (12)$$

$$\sin\theta = \tan\theta = \theta \quad (13)$$

$$\cos\theta = \frac{1}{\sec\theta} = 1.0 \quad (14)$$

$$V = U_o + u \quad (15)$$

$$v_{grd} = v \quad (16)$$

$$w_{grd} = w \quad (17)$$

$$\beta = \frac{v}{U_o} = 57.3 \quad (18)$$

$$\alpha = \frac{w}{U_o} = 57.3 \quad (19)$$

BELL HYBRID FIXED-BASE SIMULATOR (BHFB)

The BHFB simulation consists of two Pace 231-R analog computers and an IBM 7090 digital computer connected by a digital-analog data linkage system and programmed to solve the combined equations of motion of the aircraft, the control system, and the propulsion system. The hybrid approach permits a

more precise representation of the nonlinear data, which can be stored and changed independently from the control system characteristics and analytical expressions for acceleration and inertia coupling terms.

A block diagram layout of the hybrid X-22A simulation is shown in Figure 6. The major separation between the digital and analog computational blocks is shown, and the data flow between the various elements is indicated.

The digital portion of the simulation performs the following functions:

1. Control logic for mode and subroutine selection options.

2. Calculations of aerodynamic body axis forces and moments, and linear and angular accelerations.

3. Calculations of range, cross range, and altitude rates.

4. Computations of total velocity, aircraft attitudes and flight path angles, dynamic pressure, maximum thrust, thrust coefficient, and duct exit pressure.

5. Calculation of total pitch, roll, and yaw control slopes.

The analog section performs the following computations plus all integrations:

1. Linear accelerations due to gravity and rate products.

2. Angular accelerations due to cross-product terms and control.

3. Euler angle equations.

4. Control system limits and phasing with duct angle.

5. Propulsion system and SAS dynamics.

The simulation is subject to the limitations implied by the equations of motion and mechanization given below.

EQUATIONS MECHANIZED ON ANALOG COMPUTERS

Summation of Force and Moment Equations (Body Axes)

$$\dot{u} = -qw + rv - g \sin\theta + (\dot{u})_{DC} \tag{20}$$

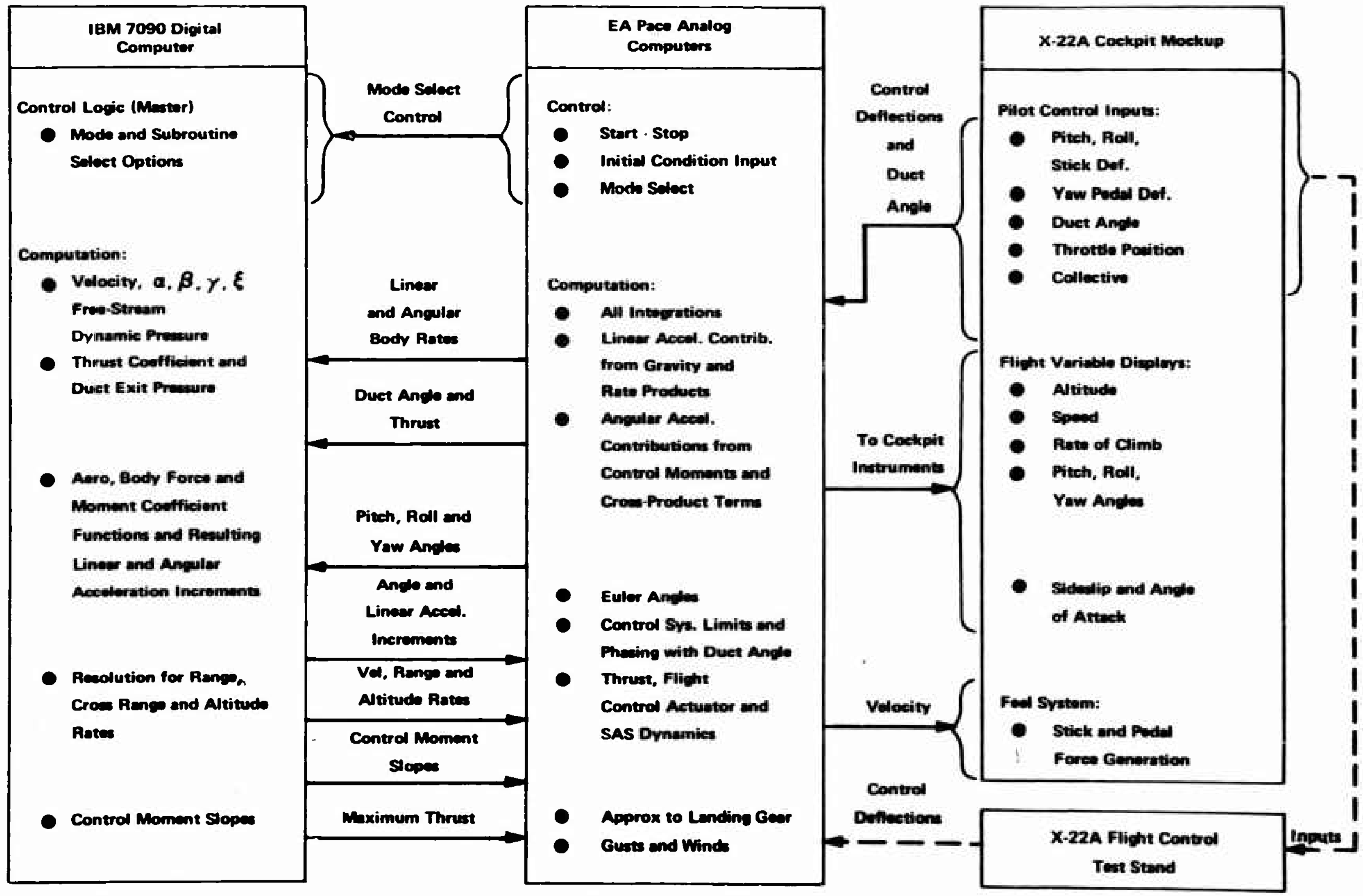

Figure 6. Functional Block Diagram of BHFB Simulation.

$$\dot{w} = -pv + qU + g \cos\theta \cos\phi + (\dot{w})_{DC} \tag{21}$$

$$\dot{v} = -rU + pw + g \cos\theta \sin\phi + (\dot{v})_{DC} \tag{22}$$

$$\dot{p} = \frac{1}{I_x}\left[I_{xz}(\dot{r} + qp) - (I_z - I_y)\, rq \right] + (\dot{p})_{DC} + \dot{p}_c + \dot{p}_{SAS} \tag{23}$$

$$\dot{q} = \frac{1}{I_y}\left[I_{xz}(r^2 - p^2) - (I_x - I_z)\, pr \right] + (\dot{q})_{DC} + \dot{q}_c + \dot{q}_{SAS} \tag{24}$$

$$\dot{r} = \frac{1}{I_z}\left[I_{xz}(\dot{p} - qr) - (I_y - I_x)\, pq \right] + (\dot{r})_{DC} + \dot{r}_c + \dot{r}_{SAS} \tag{25}$$

<u>Control Power Equations</u>

$$\dot{p}_c = \Delta\dot{p}_{\beta\,max_{DC}} \frac{\beta_{RY}}{\beta_{RY_{max}}} + \Delta\dot{p}_{F\,max_{DC}} \frac{\delta_{RY}}{\delta_{RY_{max}}} \tag{26}$$

$$\dot{q}_c = \Delta\dot{q}_{\beta\,max_{DC}} \frac{\beta_{ps}}{\beta_{ps_{max}}} \frac{\beta_{ps_{max}}}{\beta_{max\,pitch_{DC}}} + \Delta\dot{q}_{F\,max_{DC}} \frac{\delta_e}{\delta_{e_{max}}} \frac{\delta_{e_{max}}}{\delta_{e_{max_{DC}}}} \tag{27}$$

$$\dot{r}_c = \Delta\dot{r}_{\beta\,max_{DC}} \frac{\beta_{RY}}{\beta_{RY_{max}}} + \Delta\dot{r}_{F\,max_{DC}} \frac{\delta_{RY}}{\delta_{RY_{max}}} \tag{28}$$

<u>Attitude Control System Mechanization Equations</u>

$$\frac{\delta_{ps}}{\delta_{ps_{max}}} = \frac{\beta_{ps}}{\beta_{ps_{max}}} = \frac{\delta_e}{\delta_{e_{max}}} \tag{29}$$

$$\frac{\beta_{RY}}{\beta_{RY_{max}}} = \frac{\beta_{rs}}{\beta_{rs_{max}}} \frac{\beta_{rs_{max}}}{\beta_{RY_{DC}}} + \frac{\beta_{rp}}{\beta_{rp_{max}}} \frac{\beta_{rp_{max}}}{\beta_{RY_{DC}}} \tag{30}$$

$$\frac{\delta_{RY}}{\delta_{RY_{max}}} = \frac{\delta_a}{\delta_{a_{max}}} \frac{\delta_{a_{max}}}{\delta_{RY_{DC}}} + \frac{\delta_r}{\delta_{r_{max}}} \frac{\delta_{r_{max}}}{\delta_{RY_{DC}}} \tag{31}$$

$$\frac{\delta_{rs}}{\delta_{rs_{max}}} = \frac{\beta_{rs}}{\beta_{rs_{max}}} = \frac{\delta_a}{\delta_{a_{max}}} \tag{32}$$

$$\frac{\delta_{rp}}{\delta_{rp_{max}}} = \frac{\beta_{rp}}{\beta_{rp_{max}}} = \frac{\delta_r}{\delta_{r_{max}}} \tag{33}$$

$$\beta_{ps_{max}} = \begin{cases} \left(\frac{\lambda}{52.5}\right) 11 & \text{For } 0^\circ < \lambda \leq 52.5^\circ \\ 11 & \text{For } \lambda > 52.5^\circ \end{cases} \tag{34}$$

$$\delta_{e_{max}} = (90 - \lambda)/3 \tag{35}$$

$$\beta_{rs_{max}} = \begin{cases} 1.7 + \frac{\lambda}{52.5}(3.2) & \text{For } 0^\circ < \lambda \leq 52.5^\circ \\ 4.9 & \text{For } \lambda > 52.5^\circ \end{cases} \tag{36}$$

$$\delta_{a_{max}} = (90 - \lambda)/4.5 \tag{37}$$

$$\beta_{rp_{max}} = (90 - \lambda)/30 \qquad (38)$$

$$\delta_{r_{max}} = \frac{\lambda}{[illegible]} \qquad [illegible]$$

The pitch and roll stick motions were mechanized to conform to the stick pattern shown in Figure 7.

Mechanization of Thrust Control System

Power Control Mode

$$T = \left(\frac{\delta_{T_c}}{\delta_{T_{c_{max}}}} \right) T_{max} \qquad (40)$$

where T_{max} is stored in the digital computer in tabular form as a function of duct angle and forward speed, and $\frac{\delta_{T_c}}{\delta_{T_{c_{max}}}}$ is the throttle setting.

Collective Mode

$$T = \left(\frac{\beta_c - \beta_{T=0}}{\beta_{MP} - \beta_{T=0}} \right) T_{max} \quad \text{where } T \geq 0 \qquad (41)$$

The collective stick sensitivity was mechanized as a variable function of speed, according to the blade angle travel for minimum and maximum thrust presented in Figure 8.

Stability Augmentation System (SAS)

The stability augmentation system was mechanized for all axes on function generators, which programmed the damping augmentation as a function of speed.

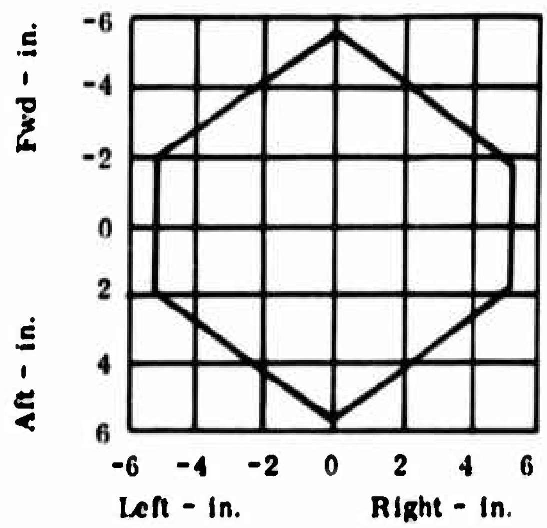

Figure 7. X-22A Pitch and Roll Control Stick Pattern.

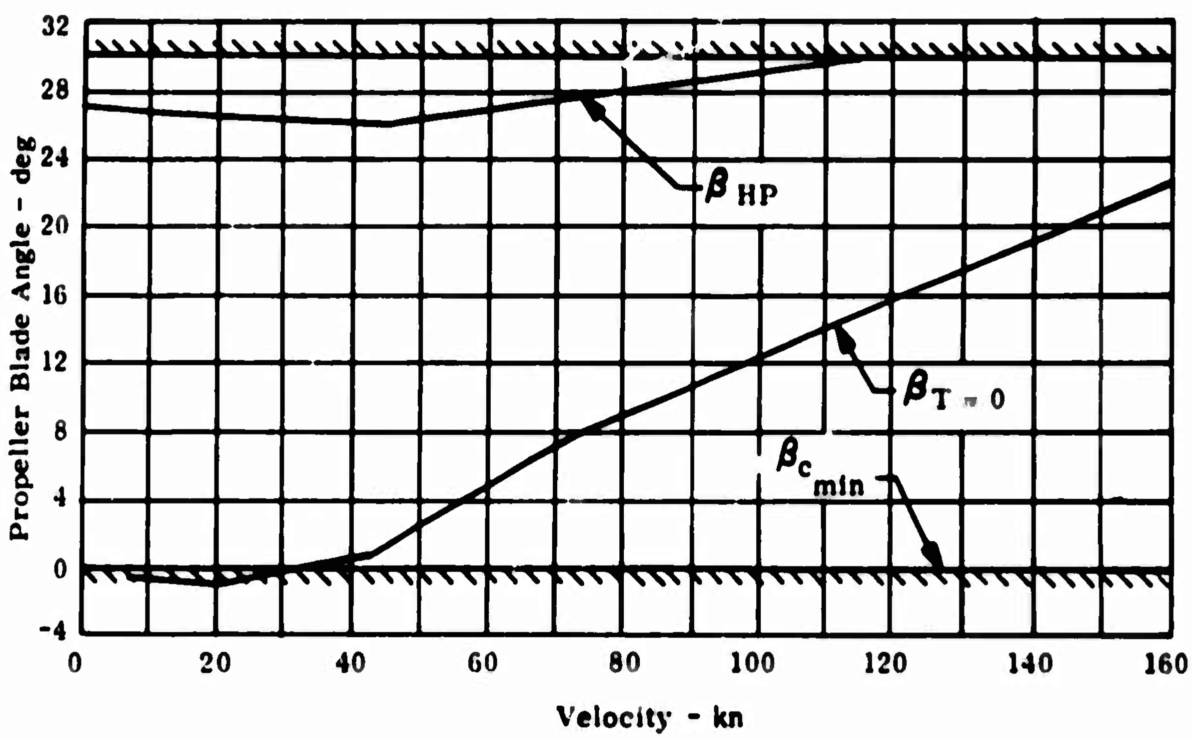

Figure 8. Propeller Blade Angle for Military Power, Zero Thrust, and Collective Limits versus Velocity.

Euler Angles

$$\dot{\phi} = p + \dot{\psi} \sin \theta \tag{42}$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \tag{43}$$

$$\dot{\psi} = (r \cos \phi + q \sin \phi)/\cos \theta \tag{44}$$

EQUATIONS MECHANIZED ON THE IBM 7090 DIGITAL COMPUTER

Aerodynamic Components of the Force and Moment Equations

$$(\dot{u})_{DC} = (C_x q_T S) / m \tag{45}$$

$$(\dot{w})_{DC} = (C_z q_T S) / m \tag{46}$$

$$(\dot{v})_{DC} = \frac{S}{m} \left[C_Y q_T + \frac{qb}{2V} \left\{ C_{Y_r} r + C_{Y_p} p \right\} - \left(\frac{346}{8100\ S} \right) p \lambda^2 \right] \tag{47}$$

$$(\dot{p})_{DC} = \frac{bS}{I_y} \left[C_{\ell} q_T + \frac{qb}{2V} \left\{ C_{\ell_p} p + C_{\ell_r} r \right\} \right.$$

$$\left. - \left\{ \left(\frac{4250}{8100\ bS} \right) p + \left(\frac{2650}{8100\ bS} \right) r \right\} \lambda^2 \right] \tag{48}$$

$$(\dot{q})_{DC} = \frac{\bar{c}S}{I_y} \left[C_m q_T + \frac{q\bar{c}}{2V} (C_{m_q} q) - \left(\frac{4130}{8100\ \bar{c}S} \right) q \lambda^2 \right] \tag{49}$$

$$(\dot{r})_{DC} = \frac{bS}{I_z} \left[C_n q_T + \frac{q}{2V} \left\{ C_{n_r} r + C_{n_p} p \right\} - \left(\frac{6670}{8100\ bS} \right) r \lambda^2 \right] \tag{50}$$

$$q = \frac{1}{2} \rho V^2 \tag{51}$$

$$V = \sqrt{U^2 + v^2 + w^2} \tag{52}$$

$$q_T = (T/S) + q \tag{53}$$

$$C_{T_s} = \frac{T}{q_T S} \tag{54}$$

$$\alpha = \tan^{-1}\left(\frac{w}{U}\right) \tag{55}$$

$$\beta = \sin^{-1}\left(\frac{v}{V}\right) \tag{56}$$

$$\gamma = \sin^{-1}\left(\frac{\dot{h}}{V}\right) \tag{57}$$

$$\xi = \tan^{-1} \frac{\dot{R}_c}{\dot{R}_g} \tag{58}$$

<u>Ground Axis Velocities</u>

$$\begin{aligned}(\dot{R}_g) = {} & U(\cos\psi\cos\theta) + v(\cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi) \\ & + w(\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)\end{aligned} \tag{59}$$

$$(\dot{h}) = U\sin\theta - v(\cos\theta\sin\phi) - w(\cos\phi\cos\theta) \tag{60}$$

$$\begin{aligned}(\dot{R}_c) = {} & U(\sin\psi\cos\theta) + v(\cos\psi\cos\phi + \sin\psi\sin\phi\sin\theta) \\ & + w(\sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi)\end{aligned} \tag{61}$$

$$C_x\,(\alpha\,,\lambda\,,C_{T_s}) \tag{62}$$

$$C_z\,(\alpha\,,\lambda\,,C_{T_s}) \tag{63}$$

$$C_m\,(\alpha\,,\lambda\,,C_{T_s}) \tag{64}$$

$$C_Y\,(C_{T_s}\,,\alpha\,,\beta\,,\lambda) \tag{65}$$

$$C_\ell\,(C_{T_s}\,,\alpha\,,\beta\,,\lambda) \tag{66}$$

$$C_n\,(C_{T_s}\,,\alpha\,,\beta\,,\lambda) \tag{67}$$

$$\left.\frac{\partial C_N}{\partial C_T}\right|_{fwd}(\lambda\,,C_{T_s}) \tag{68}$$

$$\left.\frac{\partial C_N}{\partial C_T}\right|_{aft}(\lambda\,,C_{T_s}) \tag{69}$$

$$\frac{x_{N_F}}{\bar{c}}(\lambda\,,C_{T_s}) \tag{70}$$

$$\frac{x_{N_A}}{\bar{c}}(\lambda\,,C_{T_s}) \tag{71}$$

$$C_{m_q}(\lambda\,,C_{T_s}) \tag{72}$$

$$T_{max}\left[(\alpha+\lambda),\ |V|\right] \tag{73}$$

$$C_{Y_p}\ (\alpha\ ,\lambda\ ) \tag{74}$$

$$C_{\ell_p}\left[(\alpha+\lambda),\ C_{T_s}\right] \tag{75}$$

$$C_{n_p}\ (\alpha\ ,\ \lambda\ ) \tag{76}$$

$$C_{Y_r}\ (\alpha\ ,\lambda\ ) \tag{77}$$

$$C_{\ell_r}\ (\alpha\ ,\ \lambda\ ) \tag{78}$$

$$C_{n_r}\ (\alpha\ ,\ \lambda,\ C_{T_s}\ ) \tag{79}$$

$$\frac{\partial T}{\partial \beta}(\ \lambda\ ,\ V) \tag{80}$$

Control Equation Solved by the IBM 7090 and Sent to Analog

Pitch Acceleration Due to Blade Angle

$$\Delta\dot{q}_{\beta\ max_{DC}} = \frac{-1}{I_y}\left(2\bar{c}\,\frac{\partial T}{\partial \beta}\right)\left[\left(\frac{x_{AX_F} - x_{AX_A}}{\bar{c}}\right) + 2\left.\frac{\partial C_N}{\partial C_T}\right|_{\substack{fwd\\ \alpha=0}} \frac{(x_{N_F})}{\bar{c}} - 2\left.\frac{\partial C_N}{\partial C_T}\right|_{\substack{aft\\ \alpha=0}} \frac{(x_{N_A})}{\bar{c}}\right]\Delta\beta_{max\ pitch_{DC}}\ (rad/sec^2) \tag{81}$$

Pitch Acceleration Due to Flaps

$$\Delta \dot{q}_{F_{max_{DC}}} = \frac{-1}{I_y} (0.04 - 0.000444\, \lambda)\, (q_e S \bar{c})\, \delta_{e_{max_{DC}}} \quad (rad/sec^2) \qquad (82)$$

Roll Acceleration Due to Blade

$$\Delta \dot{p}_{\beta_{max_{DC}}} = \left(\frac{-1}{I_x}\right) \left(2 \frac{\partial T}{\partial \beta}\right) \beta_{RY_{DC}} \Bigg\{ (y_F + y_A) \sin \lambda$$

$$+ 2 \left[\left. \frac{\partial C_N}{\partial C_T} \right|_{\substack{fwd \\ \delta = 0}} (y_F) + \left. \frac{\partial C_N}{\partial C_T} \right|_{\substack{aft \\ \delta = 0}} (y_A) \right] \cos \lambda \Bigg\} \quad (rad/sec^2) \qquad (83)$$

Roll Acceleration Due to Flaps

$$\Delta \dot{p}_{F_{max_{DC}}} = (-0.005 \cos \lambda)\, (q_e S b) \left(\frac{1}{I_x}\right) \delta_{RY_{DC}} \quad (rad/sec^2) \qquad (84)$$

Yaw Acceleration Due to Blade

$$\Delta \dot{r}_{\beta_{max_{DC}}} = \frac{-1}{I_z} \left(2 \frac{\partial T}{\partial \beta}\right) \beta_{RY_{DC}} \Bigg\{ (y_F + y_A) \cos \lambda$$

$$- 2 \left[\left. \frac{\partial C_N}{\partial C_T} \right|_{\substack{fwd \\ \delta = 0}} (y_F) + \left. \frac{\partial C_N}{\partial C_T} \right|_{\substack{aft \\ \delta = 0}} (y_A) \right] \sin \lambda \Bigg\} \quad (rad/sec^2) \qquad (85)$$

Yaw Acceleration Due to Flaps

$$\Delta \dot{r}_{F_{max_{DC}}} = \frac{A q_e S b}{I_z} \delta_{RY_{DC}} \quad (rad/sec^2) \qquad (86)$$

The pilot perceives flight cues in the BHFB by observing a flight information display panel situated directly in front of him. This panel contains two dual trace oscilloscopes mounted one above the other. These scopes can be programmed to represent various configurations of attitude and horizontal situation indicators. For this program, horizon and heading information was presented on the upper scope, and ground position and rate were presented on the lower scope. Attitude scope displays are limited to ±90° in roll and ±20° in yaw. The ground velocity presentation used for hover is limited to ±40 kn in the longitudinal and lateral directions. This presentation was also used in the BLFB. Additional flight parameters are displayed on 3-1/4-inch simulated flight instruments located on both sides of the scope display. These instruments are interchangeable to facilitate various instrument arrangements for research purposes.

Although the specific parameters and ranges displayed are functions of the individual simulation objectives, the ones most generally used are given in Table XV.

TABLE XV. FLIGHT PARAMETER DISPLAYS AND RANGES AVAILABLE IN THE BLFB AND BHFB COCKPITS

Display	Range
Barometric Altitude	0 to 30,000 ft
Radar Altitude	0 to 500 ft
Vertical Speed	±4000 ft/min
Airspeed	10 to 350 kn
Low-Range Airspeed	-40 to 160 kn
Flight Path Angle	-20 to +40 deg
Duct Angle	0 to 100 deg
Angle of Attack	-20 to 40 deg
Percent Thrust	0 to 160%
Propeller rpm	0 to 3000 rpm
Clock	Time
Rate of Turn	Full left or right

Visual presentation of flight cues is limited to the parameters and capability of the visual displays as described. The simulation lacks aural, vibrational, and vestibular cues. The mathematical model is considered to be the best representation possible with available data. In performing continuous transitions, a minor programming restriction to be observed is that conversion should begin at a zero or positive value of airspeed. This restriction is essentially one of procedure and does not constitute a limitation to the useful transition flight envelope.

Additional complexities that have been simulated include: representation of ground plane, ground effects, and control system lost motion and hysteresis. The ground plane equations were evaluated to be unjustifiably complex in view of the lack of aural, peripheral-vision, and vestibular cues. It was found that with sufficient practice pilots were able to develop an adequate vertical takeoff and landing technique without the ground plane, by using a combination of the information provided by altimeter and the vertical speed indicator (VSI). Since without a ground plane, the VSI reads negative for thrust levels less than the weight (i.e., unrealistic readings before takeoff and after landing), the pilot must provide compensation. For takeoff, he compensates by gradually increasing thrust and speed until the VSI reads positive, which is the indication of takeoff. For landing, he reduces thrust and monitors the altimeter and the VSI, keeping the VSI within landing gear design limits until the altimeter reads zero, which is the indication that the landing is completed. Nonlinear ground effects in fixed base were evaluated to be unrealistic. There were no discernible effects on the performance of vertical landings and takeoffs.

Effects of lost motion and hysteresis in the control system, on flight characteristics in hover and transition, were evaluated in the simulator, using data results from tests of the actual flight hardware. The pilots were annoyed by minor effects on their ability to control attitude, but in general they felt that the overall burden of the hover and transition work load was not increased significantly. These effects were then deleted to conserve equipment. Gusts were not represented in the BHFB, because, after flying the aircraft, the pilots felt that the simulator was already difficult enough to fly relative to the aircraft, and that the inclusion of gusts would add to the work load and would widen this disparity with respect to flight.

AMES LINEARIZED MOVING-BASE SIMULATION (ALMB)

The ALMB simulation was originally mechanized on analog computers. Although still essentially the same, it has since been converted to a hybrid program implemented on two EAI 231-R analog computers and one EAI 8400 digital computer, in accordance with the Ames long-range simulator improvement program.

The aircraft equations of motion and the real-time coordinate transformation equations are programmed on the digital computer portion. The analog computers are used to generate the aerodynamic and control forces and moments and to drive the simulator and the information displays. Motion computation is exact and is done in body axes. Motions are than transformed into simulator gimbal angle, inertial space, and Euler angle drives, which are used by the simulator to drive the cockpit.

The configuration of the attitude controls was generally representative of the X-22A. Pitch and roll stick force gradients were obtained with an undamped bungee feel system. Control forces and travels were adjusted to conform to X-22A values. Overall, the simulator control characteristics were similar to those of the X-22A and were generally acceptable.

The attitude control stick moved easily and smoothly and returned to center quickly when released. A pitch and roll attitude trim switch located on top of the stick was not operative. However, a duct rotation switch on the collective stick was used to trim pitch attitude when desired. This trim characteristic differed from the X-22A, which can trim stick forces in any stick position; the difference does not constitute a significant simulator limitation.

Rudder pedals operated smoothly and stayed where set because there was no pedal force gradient or positive centering. Pedal breakout and friction forces were generally similar to those of the X-22A in hover; the X-22A has usually been flown without a force gradient in yaw.

The collective stick was mounted on the left side of the cockpit as in the aircraft. Because there is an appreciable variation with forward speed of power applied per unit of propeller blade angle in the X-22A, the control sensitivity of the collective stick increases significantly. These characteristics were accurately represented in the simulator by using appropriate values at each fixed operating point flight condition investigated, but the linearized collective stick sensitivity gradient, with respect to speed, was assumed to be negligible. This simplification has no significant influence in hover and transition for the range of speeds away from trim investigated.

The ALMB used essentially the same equations of motion, hover derivatives, and system characteristics as used for the BLFB, and it has the same inherent mathematical and information display limitations. Aerodynamic stability and control derivatives were linearized from the nonlinear data as programmed in the BHFB simulation.

The essential differences between the two mathematical models are the gimbal drive equations and the wind, gusts, and ground effect models, which were included primarily because of the ALMB motion capability. Other differences between the mathematical models are that in the ALMB, angles are calculated without using small-angle approximations, and body axis motions are transformed into the inertial space axis system to operate the gimbal angle drives. The following equations of motion are written as programmed for the ALMB simulator.

Equations Mechanized on Analog Computer

Equation of Motion (Body Axes)

$$\ddot{X}_A = X_{A/m} = (X_o + X_u u + X_w \Delta w + T\cos\lambda)/m \tag{87}$$

$$\ddot{Y}_A = Y_{A/m} = (Y_v v + Y_p p + Y_r r)/m \tag{88}$$

$$\ddot{Z}_A = Z_{A/m} = (Z_o + Z_u|u| + Z_w w + Z_v|v| - T\sin\lambda)/m \tag{89}$$

$$\dot{p}_A = L_{A/I_x} = \Big[L_v v + L_{p_{Aero}} p + L_r r + L_{p_{SAS}} p + L_{\delta_{rs}} \delta_{rs} + L_{\delta_{rp}} \delta_{rp} + L_{\delta_{rp_u}} \delta_{rp} u + L(h/D,\phi) \Big] /I_x \tag{90}$$

$$\dot{q}_A = M_{A/I_y} = (M_o + M_u u + M_w w + M_{q_{Aero}} q + M_{q_{SAS}} q + M(h/D,\phi) + M_{\delta_{ps}} \delta_{ps})/I_y \tag{91}$$

$$\dot{r}_A = N_{A/I_z} = (N_v v + N_p p + N_{r_{Aero}} r + N_{r_{SAS}} r + N_{\delta_{rp}} \delta_{rp}(K_{GE}) + N_{\delta_{rs}} \delta_{rs} + N_{\delta_{rs_u}} \delta_{rs} u)/I_z \tag{92}$$

where $K_{GE} = f(h/D)$

$$T/m = (T_\beta/m)(\beta_c - \beta_{T=0})\Big[1 + f(h/D,\beta)\Big] \tag{93}$$

where T/m is zero for $\beta_c \le \beta_{T=0}$

Equations Mechanized on Digital Computer

$$\ddot{X} = \ddot{X}_A - g \sin \theta + rv - qw \tag{94}$$

$$\ddot{Y} = \ddot{Y}_A + g \cos\theta \sin \phi - rU + pw \tag{95}$$

$$\ddot{Z} = \ddot{Z}_A + g \cos\theta \cos \phi + qU - pv \tag{96}$$

$$\dot{p} = \dot{p}_A - \left(\frac{I_z - I_y}{I_x}\right) qr + \left(\frac{I_{xz}}{I_x}\right) (\dot{r} + qp) \tag{97}$$

$$\dot{q} = \dot{q}_A - \left(\frac{I_x - I_z}{I_y}\right) rp + \left(\frac{I_{xz}}{I_y}\right) (r^2 - p^2) \tag{98}$$

$$\dot{r} = \dot{r}_A - \left(\frac{I_y - I_x}{I_z}\right) pq + \left(\frac{I_{xz}}{I_z}\right) (\dot{p} - qr) \tag{99}$$

$$\dot{\phi} = p + \tan \theta (q \sin \phi + r \cos \phi) \tag{100}$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \tag{101}$$

$$\dot{\psi} = (r \cos \phi + q \sin \phi)/\cos \theta \tag{102}$$

$$\alpha = \tan^{-1} \left(\frac{w}{U}\right) \tag{103}$$

$$\beta = \tan^{-1} \left(\frac{v}{\sqrt{U^2 + w^2}}\right) \tag{104}$$

$$V = \sqrt{U^2 + v^2 + w^2} \tag{105}$$

Body-Axis-to-Inertial-Axis Transformation

All computations are done in body axes and transformed into inertial or ground axes through the following matrix.

$$\begin{array}{c}\begin{vmatrix} A_x \\ A_y \\ A_z \end{vmatrix}_{\text{Body}} = \begin{vmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi & \cos\theta\sin\phi \\ \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi & \sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi & \cos\theta\cos\phi \end{vmatrix} \begin{vmatrix} A_x \\ A_y \\ A_z \end{vmatrix}_{\substack{\text{Inertial} \\ \text{(Ground)}}}\end{array} \tag{106}$$

Transformation of Winds and Gusts

Winds and gusts are introduced as velocity inputs in the inertial axis system and transformed into the body axes by the following matrix.

$$\begin{vmatrix} U \\ v \\ w \end{vmatrix}_{\text{Inertial}} = \begin{vmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{vmatrix} \begin{vmatrix} U \\ v \\ w \end{vmatrix}_{\text{Body}} \tag{107}$$

Representation of Winds and Gusts

A gust model developed as the result of automatic landing system studies was used in the ALMB to simulate low-altitude and ground effect turbulence. This model expresses the gust power spectral density as

$$PSD(w_g) = \frac{2L\,\sigma_g^{\,2}}{\pi\bar{V}} \left| \frac{1}{\left(\frac{L}{\bar{V}}\right)(j\omega + 1)} \right|^2 \tag{108}$$

Early trials used a value for rms gust velocity, σ_g, of $\bar{V}/4$, which was unanimously judged to be much more severe than ever experienced in flight. Further evaluation at lower values of σ_g indicated that $\bar{V}/8$ to $\bar{V}/10$ is a better approximation of actual conditions; these lower values were used throughout the program.

APPENDIX II
DATA COMPILATIONS OF PILOT RATINGS AND COMMENTS

This appendix contains compilations of individual pilot ratings and comments from the various simulations and flights (Tables XVI through XXV). Data are classified in major categories by flight regime and compiled in subcategories by flight task so that there is a task-by-task relationship between simulator and flight results. The data presented were compiled directly from the raw data and have not been adjusted or interpreted for differences in FULL SAS levels between simulations which are listed in Table IV.

TABLE XVI. COMPILATION OF PILOT RATINGS AND COMMENTS FOR HOVER HEIGHT CONTROL				
Case	SAS	RCR	Pilot	Comment
BLFB (6 DOF)	FULL	3.5-4	F	Height control comparable to aircraft but slightly more difficult, probably due to concentration on attitude. Less effort to climb than to translate, since thrust required varies with speed. Simulator resembles aircraft but requires more thrust change with speed. Initiation and stabilization of climb and descent were comparable to aircraft. Tendency to overshoot or PIO. Termination seemed slow compared to flight and was rated inferior. There was a slight tendency to overshoot but no tendency to PIO.
	1/2	4-5	F	Noticeably less attitude damping. More difficult with 1/2 SAS, probably due to concentration on attitude.
	FULL	3-4	H	Similar to aircraft. Climbs and descents were initiated and stabilized quickly in a manner similar to the aircraft with no interactions in pitch and roll. Vertical rates easily arrested (RCR 2-3). Descents were more difficult to stop in the simulator (RCR 5). The tendency to overshoot the target altitude was objectionable and resulted in a mild tendency to PIO (RCR 4).
	1/2	4-5	H	Thrust control activity is high in turn maneuvers and lateral translations. With 1/2 SAS, more concentration is required (RCR 5). Thrust response and overall performance of climb and descent average (RCR 3). Slight overshoot in climb and objectionable overshoot in descent. Tendency to PIO. Pilot able to compensate.
BLFB (3 DOF)	FULL	3.5-4	F	Same general comments as for 6 DOF. Climb and descent possibly easier due to fewer degrees of freedom.
	1/2		F	Slight degradation with 1/2 SAS but not enough to affect ratings. Climb and descent with 1/2 SAS not as difficult as 6 DOF.
	FULL	2-3	H	3-DOF task unrealistically easy. Same general comments and ratings as for 6 DOF for FULL and 1/2 SAS.
	1/2	3-4	H	
ALMB	FULL	2	B	Similar to aircraft, collective position for hover uncomfortable, no attitude interactions with collective noted. Collective would not stay where set, making task more difficult than in aircraft (RCR 4).
	FULL	4	C	Thrust control inferior due to poor combination of collective friction and sensitivity; also some free play. No appreciable degradation with gusts.
	1/2	5	C	Slight further degradation with gusts (ΔRCR = -1.0)
	FULL	4	E	Thrust control activity excessive and altitude control inferior. Major pilot effort required to hold ±6 ft. Height damping more noticeable in simulator than in aircraft. n_z response to collective step almost identical to aircraft. Changes in pitch attitude due to thrust control are small.
	1/2	5	E	Arduous task with winds plus high-intensity gusts. No attitude coupling with thrust. Gusts mask vertical acceleration cues due to control. Initial response to climb and descent commands rated normal with superior vertical rate stabilization (RCR 3). Ability to terminate climbs and descents was average, with slight tendency to overshoot and PIO. With winds and gusts, overshoot and PIO tendencies were objectionable (RCR 6).
	0	7	E	Increased pilot effort over 1/2 SAS. 5-kn head wind and minimum gust levels controlled.
	FULL	3	F	Height control characteristics rated normal. Climb and descent initiation, level-off, and control response rated average. No tendency to overshoot or PIO.
	1/2	3	F	Rating given is without gusts. Rating with gusts is degraded to RCR 6.
	0	5	F	Rating given is without gusts. Rating with gusts is further degraded to RCR 8.
	FULL	4	G	Simulator was more responsive to down collective and easier to get a satisfactory descent rate in than aircraft. Slight increase in vertical rate damping would reduce pilot effort and improve rating. Control activity was slightly above a good helicopter, but even most helicopters require too much effort for RCR 3.
	1/2	-	G	As SAS decreases, height control task remains the same, but because pilot concentrates more on attitude control task, wider variations in height are experienced at reduced SAS levels.
	FULL	2-3	H	Thrust control activity for hover rated low, altitude control superior. Dead band in collective stick near trim is unrealistic. Ability to initiate climbs and descents rated superior due to fast response to control inputs. A mild tendency to overshoot final altitude resulted in slight PIO tendency. Ability to level off rated average.
	1/2	3-4	H	Thrust control activity rated normal; altitude control average. Climb and descent task rating downgraded approximately 1 unit from full SAS.

TABLE XVI (CONT)				
Case	SAS	RCR	Pilot	Comment
BHFB	FULL	4-5	A	Insufficient cues, best cue is vertical rate.
	FULL	5	B	Height control activity rated excessive. Task made more difficult by lack of hand support.
	FULL	4-5	C	Altitude very difficult to hold without concentration. Collective control will not stay set. Vertical control axis rated inferior to average.
	FULL	5-6	D	Height hard to judge due to insufficient vertical cues. Attitude interactions due to thrust control are minimal. Height control and ability to control rates of climb and descent rated inferior with FULL SAS.
	0	7-8	D	Height control and ability to hold rates of climb and descent rated poor with NO SAS
	FULL	-	E	Ability to hold altitude poor, ability to climb and descend average.
	FULL	3	F	Height control rated normal as compared to aircraft. No problem in climbing or descending.
Flight	FULL	2	B	Height control average. Lack of centering in collective noted. Ability to climb and descend rated average.
	FULL	3-4	C	Pilot developed a damped vertical PIO of large amplitude which he attributed to combination of poor visibility, collective stick sensitivity, and lack of power indicator.
	FULL	-	D	Accurate control of rate of climb and descent rated poor to inferior (RCR 4-5). Difficult to control climb through ground effect (RCR 4). Rate of descent still harder to control (RCR 5).
	FULL	5	E	Height control poor; prolonged effort to stabilize.
	FULL	4	F	Control within ±3 feet is relatively easy task. Tight height control (±1 ft) is difficult (RCR 6). Slight increase in activity with fwd or lateral speed (ΔPR = -1.0). Very good thrust response. Rates of climb and descent can be established and held or stopped as required for typical flight maneuvers.
	FULL	4-6	G	Height control activity high. Controllability rated inferior to average (RCR 4-6). Difficult to control vertical rates and altitude OGE, possibly because of poor visibility at high hover height flown. Inferior to average. Descent rate hardest to control (RCR 4-6). Controllability deteriorates further IGE. PIO developed twice (RCR 9).
	FULL	3-4	H	Requires attention to maintain height. Not too much variation of height with speed in and around hover. Ability to initiate and stabilize climb and descent rated average. Ability to terminate rated inferior for climb (RCR 3) and superior for descent (RCR 2). No tendency to overshoot noted in descent. Overshoot tendency in climb is mild. Slight tendency to PIO rated RCR 4.

TABLE XVII. COMPILATION OF PILOT RATINGS AND COMMENTS FOR HOVER ATTITUDE CONTROL ACTIVITY (PITCH, ROLL, YAW)

Case	Axis	RCR SAS Full	RCR SAS 1/2	RCR SAS 0	Pilot	Comment
BLFB (6 DOF)	P	2	3	-	F	Representative of X-22A in pitch and roll.
	R	3	4	-	F	
	Y	4	4	-	F	Simulator difficult to trim in yaw.
	P	3	4	-	H	Pitch activity minimal for hover, climb, and descent; low for forward and lateral translations.
	R	3	4	-	H	Roll activity minimal for hover, climb and descent, and forward translation, increasing to high for lateral translations.
	Y	4	5	-	H	Yaw is more difficult to keep within ±5° than aircraft, and activity is high for lateral translations.
BLFB (3 DOF)	P	3	3	-	F	Slight degradation in handling qualities with 1/2 SAS but not enough to affect Cooper ratings.
	R	3	3	-	F	
	Y	3	3	-	F	
	P	2	2	-	H	Unrealistically easy; minimal pitch activity in climb and descent. No interaction due to power.
	R	3	3	-	H	Roll activity low for climb and descent, high for forward translation, and excessive for lateral translation with 1/2 SAS.
	Y	4	4	-	H	Yaw control activity is high, particularly for lateral translations with 1/2 SAS.
ALMB	P	1	-	-	B	Very similar to actual aircraft. No control interactions of any significance noted.
	R	1	-	-	B	Control activity minimal in all axes with FULL SAS
	Y	1	-	-	B	
	P	2	4	-	C	Pitch and roll activity rated normal with FULL SAS; high with 1/2 SAS.
	R	2	4	-	C	
	Y	1	3	-	C	Yaw activity rated minimum to low with FULL SAS; normal with 1/2 SAS
	P	3	3	5	F	Gust levels generally too high. Aircraft not nearly as sensitive to gusts. Best representation of average flight condition is 1/2 low level gust. Slight degradation of handling qualities in all axes with 1/2 SAS.
	R	3	3	5	F	Gusts degrade ratings to RCR 6 for 1/2 SAS and RCR 8 for NO SAS.
	Y	2	3	5	F	
	P	3-4	4	6-7	G	Pitch and roll control activity rated high, becoming excessive as SAS decreases. No couplings noted (RCR 1). Attitude response very fast in pitch and roll. Attitude control rated average near trim. Speed control rated poor due to lack of force trim. Noseup easier to control than nosedown which was more uncomfortable and harder to determine proper input to correct disturbances. Yaw control activity rated minimal.
	R	3-4	4	6-7	G	
	Y	1	4	4	G	
	P	2	4	-	H	Low activity with FULL SAS and high with 1/2 SAS.
	R	2	4	-	H	Same as pitch.
	Y	2	3	-	H	Minimal with FULL SAS, increasing to normal with 1/2 SAS.
BHFB		4	-	-	A	Pitch control activity rated normal for hover task; no unusual control couplings.
		5	-	-	A	Roll activity high due to lack of physical cues.
		3	-	-	A	Best control axis; excessive trim drift.
	P	3	-	-	B	Control activity for both pitch and roll was rated low. Spot hover relatively easy.
	R	3	-	-	B	Slight tendency to cycle lateral control in PIO of 2 cps which disappeared with practice.
	Y	6	-	-	B	Yaw control task made unrealistically difficult due to nature of display. Yaw activity rated excessive.

TABLE XVII (CONT)						
		RCR				
		SAS				
Case	Axis	Full	1/2	0	Pilot	Comment
BHFB	P	2-3	2-3	5	C	Ability to hold forward speed average.
	R	3	4	6	C	Ability to hold lateral speed inferior.
	Y	2-3	3	3	C	Superior; control couplings difficult to determine because height was seldom stabilized.
	P	5	-	7	D	Pitch activity rated normal; control cross-couplings low in all axes.
	R	7	-	9	D	Roll activity rated excessive.
	Y	6	-	7	D	Yaw control activity rated high.
	P	-	-	-	E	Pitch control activity rated high, ability to translate average.
	R	-	-	-	E	Roll activity rated excessive.
	Y	-	-	-	E	Yaw control poor and not considered to be representative of aircraft due to display and trim drift.
	P	3	-	-	F	Ability to hold forward speed average.
	R	4	-	-	F	Roll control task slightly harder when stabilizing heading off-wind.
	Y	3	-	-	F	Yaw trim difficult to achieve; otherwise, control activity to hold heading average.
Flight	P	1	-	-	B	Steady hover was relatively easy. Pitch activity was rated low. Pilot effort in roll and yaw rated normal.
	P	3	-	-	C	Pitch and roll activity normal OGE and high IGE.
	R	3	-	-	C	Yaw due to roll control considered to be normal.
	Y	2	-	-	C	Yaw control in ground effect slightly higher. Height and roll coupling due to yaw control rated low.
	P	5	6	5	D	Visibility for spot hover limited by high forward instrument panel. Pitch attitude trim with ducts (RCR 3).
	R	5	-	5	D	Roll control sensitive; high pilot effort in this axis. Possibly slight right yaw with left roll rate (RCR 3). No yaw due to lateral speed (RCR 1).
	Y	3	-	5	D	Mild loss of height with yaw inputs. No SAS ratings are for very low fwd and lateral velocities (i.e., small influence of aeropropulsive speed derivatives).
	P	2	-	-	E	Attitude and directional controls very effective; minimum effort required in steady hover.
	R	2	-	-	E	
	Y	2	-	-	E	
	P	3	-	-	F	Attitude relatively easy to maintain. Yaw axis is best. Control more difficult IGE in pitch and roll (RCR 5) and yaw (RCR 4).
	R	3	-	-	F	
	Y	3	-	-	F	
	P	3-4	-	-	G	Pitch activity rated normal; roll normal to high and yaw normal to low.
	R	4-5	-	-	G	Aircraft easy to control, but very fast attitude response is somewhat undesirable.
	Y	3	-	-	G	Pitch and roll ratings degrade IGE to (RCR 5) and (RCR 7). Yaw rated same IGE.
	R	3	-	-	H	Pitch control activity rated normal with some tendency to overpower SAS.
	R	2	-	-	H	Roll control activity for steady hover task is low.
	Y	3	-	-	H	Yaw control rated normal.

TABLE XVIII. COMPILATION OF PILOT RATINGS AND COMMENTS FOR FORWARD TRANSLATIONS (CONTROL OF PITCH, ATTITUDE AND SPEED)

Case	SAS	RCR	Pilot	Comment
BLFB (6 DOF)	FULL	-	F	Thrust change with speed higher than in aircraft (i.e., increase power to increase speed).
	1/2	-	F	Simulator loses control of altitude in rapid aft translation.
	FULL	3	H	Average for speed control and superior for attitude control. Fast initial response with a mild overshoot and slight PIO tendencies on recovery. Requires increase in thrust with speed to hold altitude.
BLFB (3 DOF)	FULL	3	F	Normal response to control; no tendency to overshoot or PIO.
	1/2	3	F	Very little difference from FULL SAS. Pilot compensates when control task is simplified.
	FULL	2	H	Unrealistically easy. Fast response to pitch control with mild tendency to overshoot and PIO but not objectionable.
ALMB	FULL	2	B	Rating applies in and around hover. Increased pilot compensation required with increased attitude to overcome PIO tendencies. Degrade ratings by $\Delta PR = 2.0$ at $\theta = -25°$. No degradation if duct trim is used. Initial response to control was rated slow, although ability to initiate,
			B	stabilize, and terminate translations was rated superior.
	FULL	3	C	Good simulation of airplane. Overshoot and PIO tendencies slight to mild (RCR 4) with gusts.
	1/2	4		Overshoot and PIO tendencies mild to objectionable (RCR 4) with gusts.
	FULL	2-3	E	Rearward attitude excessive for velocity. Simulator seems to accelerate beyond point where aircraft should reach steady state. Superior ability to initiate translation but termination inferior. Objectionable tendency to overshoot results in mild PIO tendency (RCR 4).
	1/2	3	F	Same comments as above. Gusts further degrade rating (RCR 5).
	FULL	3	F	Similar to aircraft. Ducts used to trim at higher forward speeds. No overshoot tendency.
	1/2	3		Slight degradation without gusts. Degrade to RCR 6 with gusts.
	FULL	3	G	Attitude control task resembles aircraft. Static match appeared to be good. Difficult to stabilize speed with stick position near trim due to breakout. Better away from trim. Initial response to control input rated very fast (RCR 5). Pulse-type control (i.e., pulse to start pitch change and equal opposite pulse to stop) used to make attitude changes gave tendency to overcontrol (PIO). Did not like it. Forward acceleration and speed control using duct rotation quite nice; rated superior to average (RCR 2-3). Response to gusts (RCR 1).
	1/2	4	G	
	0	6-7	G	Pitch attitude with NO SAS controllable near trim using pulse-type control (RCR 4). Much more difficult away from trim (RCR 6). Noseup easier than nosedown which was more uncomfortable and harder to determine proper control input to correct disturbances. RCR 6 near trim and RCR 7 away from trim.
	FULL	2-3	H	Superior speed control and initial attitude/speed response. Mild tendency to overshoot and PIO.
	1/2	4	H	Fast initial response to pitch control. Ability to terminate translation is inferior with objectionable tendency to overshoot and PIO (RCR 5).
BHFB	FULL	3	B	Average for holding pitch attitude and steady forward speed. Steady translations in calm wind (RCR 2).
		3	C	Ability to control forward speed and attitude rated inferior to average. Increasingly worse as SAS is reduced.
		2	D	Ability to hold speed once attitude is achieved is rated superior. Marked degradation with NO SAS (RCR 6).
		-	E	Ability to translate and maintain forward speed rated average.
		3	F	Translations can be made at steady forward speeds without difficulty.
Flight	FULL	2	B	Ability to make forward translation is average.
		2-3	C	Rated for stick control. Duct rotation not used. Initiation and termination rated superior. Stabilization rated average. Slight tendency to small-amplitude PIO at 1 cps.
		3	D	Stick position demands a linearized velocity, but task rated inferior because control sensitivity makes attitude hold task difficult. Objectionable PIO noted (RCR 6). Task without attitude hold requirement rated superior to excellent (RCR 2). Height gain noted with forward speed (RCR 4). Noseup pitching moment (RCR 5) and height gain (RCR 4) noted with increased forward speed. Both undesirable for hover.
		3	E	Forward stick and duct rotation both increase forward speed. Pilot prefers duct control (RCR 2). Duct buzz heard and felt at $\lambda = 80°$ and V = 20 kn. Noise level very uncomfortable.
		3	F	Translation easily accomplished. High nosedown attitudes uncomfortable. Preferable to rotate ducts for trim if speed is to be maintained for any length of time. Speed control is good.
		4	G	Average to superior to start and stop. Harder to maintain steady over long distances. Degrades IGE (RCR 6).
		3	H	Ability to initiate translation rated inferior (RCR 4). Ability to stabilize trim and termination capability average (RCR 3). Fast initial response, with slight tendency to overshoot, but no PIO noted (RCR 2).

TABLE XIX. COMPILATION OF PILOT RATINGS AND COMMENTS FOR LATERAL TRANSLATIONS (CONTROL OF ROLL ATTITUDE AND LATERAL SPEED)

Case	SAS	RCR	Pilot	Comment
BLFB (6 DOF)	FULL	3	F	Normal aircraft response to control input. No overshoot or PIO tendencies. Height control slightly more difficult.
	1/2	4	F	Roll control activity rated high. Slight tendency to overshoot and PIO.
	FULL	3	H	Control activity rated high, and ability to hold lateral speed or attitude rated average.
	1/2	4	H	Roll control activity noticeably greater than FULL SAS. Ability to hold speed rated average but ability to hold attitude rated inferior.
BLFB (3 DOF)	FULL	3	F	Normal aircraft response to control input. No overshoot or PIO tendencies.
	1/2	3	F	Only slight degradation from FULL SAS, qualitatively same ratings. Pilot compensates for damping because control task is simpler in 3 DOF.
	FULL	3	H	Height control difficult. Initiation of translation is fast, with a mild tendency to overshoot and a slight tendency to PIO, which were not objectionable.
	1/2	4-5	H	Initiation of translation is fast with increased tendency to overshoot, which was objectionable, and a mild but not objectionable tendency to PIO.
ALMB	FULL	2	B	Control task to stabilize translation increased substantially with speed due to lack of roll attitude trim (RCR 5 at 25 kn). Other comments same as for fwd/aft translations.
	FULL	1-2	C	With gusts, ability to stabilize was average, with slight tendencies to overshoot and PIO (RCR 3). Lateral trim would help very much at higher lateral speeds. Attitude control with lateral gusts very objectionable.
	1/2	1-2	C	With gusts, ability to stabilize was inferior with mild to objectionable overshoot and PIO tendencies (RCR 5).
	FULL	2	E	See comments on fwd/aft translations.
	1/2	3	E	Same. Stabilized translation more difficult with gusts and rating degrades to (RCR 4-5).
	FULL	3	F	See comments on fwd/aft translations.
	1/2	3	F	
	0	5	F	
	FULL	3-4	G	In translating at 15 kn or more, attitude was uncomfortable and pilot activity increased (RCR 4). Hard to hold position in winds over 15 kn. Gusts were felt linearly and not angularly.
	1/2	4	G	Other comments similar to those for forward translation task.
	0	7	G	
	FULL	2-3	H	See comments for fwd/aft translations.
	1/2	4	H	
BHFB	FULL	4	C	Ability to hold lateral speed rated inferior, increasingly worse as SAS is reduced.
		2	D	Ability to hold lateral speed once attitude has been achieved was rated superior. Marked degradation with NO SAS (RCR 6).
		-	E	Ability to hold lateral speed rated inferior.
		4	F	Inferior ability to hold both lateral speed and attitude.
Flight	FULL	2	B	Ability to make lateral translations rated average.
		2-3	C	Ability to initiate and terminate rated superior. Ability to stabilize rated average.
		2	D	Lateral translation rated superior to excellent, without requirement to stabilize attitude. Increasing lateral stick displacement required with lateral velocity. Initial response is fast, with a small-amplitude PIO tendency (RCR 5). Good speed damping, but bank angles are high. Task of stabilizing at attitude rated poor (RCR 5).
		3	E	Pilot effort for attitude stabilization task is greater than for forward translation. Initial response fast, with an objectionable tendency to PIO (RCR 5). Stabilizing at speed requires a small amount of pedal.
		3	F	Translation is easily accomplished. Steady speed is easily developed and maintained.
		2-3	G	Lateral translation rated superior, but lateral speed harder to control than forward speed. Rating degrades IGE (RCR 5-7).
		3-4	H	Initiation and stabilization rated inferior (RCR 4). Ability to terminate rated superior (RCR 3). No tendencies to overshoot or PIO were noted.

TABLE XX. COMPILATION OF PILOT RATINGS AND COMMENTS FOR HOVERING TURN PERFORMANCE				
Case	SAS	RCR	Pilot	Comment
BLFB (6 DOF)	FULL	3	F	Precise heading control difficult because of simulator trim drift. Ability to turn rated average.
	1/2	4	F	Slight degradation reduces rating to inferior. Compensation is no problem. Very good control.
	FULL	3	H	Yaw control is more difficult in simulated hover than in flight but becomes easier at forward speed.
	1/2	4	H	Turn performance inferior with 1/2 SAS. Mild tendencies to overshoot and PIO. Turn initiation is good (RCR 2).
BLFB (3 DOF)	FULL	3	F	Slight overshoot tendency; no PIO.
	1/2	3	F	No appreciable degradation with 1/2 SAS detected.
	FULL	3	H	Fast response to rudder input, with mild tendency to overshoot and slight tendency to PIO, which are not objectionable.
	1/2	4	H	Turn more difficult to stabilize and terminate. Initiation is fast, with mild tendency to overshoot and slight tendency to PIO.
ALMB	FULL	1-2	B	No problem; slight degradation due to gusts (RCR 2). Initial response to control input seemed slow, and ability to initiate rated inferior. Ability to stabilize and terminate turns rated average. Slight overshoot tendency and no PIO tendency noted. Handling in turns quite similar to aircraft.
	FULL	2	C	Turn maneuver rated superior on all counts. Very slight overshoot, if any, with no significant effects of gusts on turn performance. No PIO tendencies.
	1/2	3	C	Rating lower primarily because of increased control task in other axes.
	FULL	3	E	Initial response to rudder pedal was slow, and ability to initiate turn was rated average to inferior. Ability to stabilize and terminate was rated superior. Slight overshoot and PIO tendencies.
	1/2	3	E	Initiation and stabilization poor with gusts.
	FULL	3	F	Difficult task to evaluate because of limited yaw angle travel.
	1/2	3	F	Pilot compensation not difficult.
	0	5	F	Pilot work load much increased.
	FULL	1.5	G	Yaw control is best axis. Ability to make turns rated excellent. Would be RCR 1 with a little more control effectiveness. Had to use quite a bit of control to get big rates or rapid turns (RCR 3), but rates obtained were fast enough. Stop on heading was very good.
	1/2	4	G	Drift starts right away, and pilot must enter loop to hold heading.
	0	4	G	Easily controlled for yaw task. Initial response to rudder was fast, with mild tendency to overshoot and slight tendency to PIO. Ability to initiate and terminate rated average, and ability to stabilize rated inferior.
	FULL	3	H	Initial response to rudder pedal seemed slow, with average ability to initiate and terminate turns. Ability to stabilize new heading rated superior. Slight tendency to overshoot and PIO noted.
	1/2	4	H	Initial response to rudder pedal was rated normal. Mild but not objectionable tendencies to overshoot and PIO made ability to stabilize and terminate maneuvers inferior.
BHFB	FULL	4	F	Not a good simulator task. Not representative of flight.
Flight	FULL	2-3	C	360° turns accomplished with relative ease in spite of a 12 kn crosswind.
		2-3	D	Steady turn rate out of wind developed for constant pedal position. No indication of pedal reversal. Wind effects appear at approx. 45° yaw and increase turn rate.
		3	E	Steady turn produced by fixed pedal input. No pedal reversal evident. Turn rate satisfactory. Wind effects increase turn rate after about 45° of yaw.
		3	F	Relatively easy to accomplish in winds up to 10-15 kn (RCR 3). Above that, duct rotation is helpful to relieve uncomfortable pitch attitudes due to head and tail winds in the turn (RCR 4).
		2	G	Superior turn capability in hover.
		2-3	H	Turn capability rated average. Pedal response is normal, with slight tendency to overshoot and PIO.

TABLE XXI. COMPILATION OF PILOT RATINGS AND COMMENTS FOR HOVER IN GROUND EFFECT				
Case	SAS	RCR	Pilot	Comment
ALMB	FULL 1/2 0	3 - -	B B B	Ground cushion was positive but less noticeable than flight. Combined longitudinal and lateral gusts produce linearized body accelerations rather than angular changes, which is representative of flight. Steady winds up to 5 kn do not degrade Cooper rating. Higher head winds trimmed with ducts rated RCR 4. Degraded rating primarily due to uncomfortable attitude and lack of stick force trim, rather than to a more difficult control task. Head winds not trimmed with ducts and lateral winds above 5 kn rated RCR 6.
	FULL	4	E	Descent characteristics not unlike flight. Stabilized hover IGE at approximately 3 ft (fairly representative). Bobbing effect should be more pronounced. Low-level x-y gusts provide a fair representation of turbulence in ground effect. Rating without gusts (RCR 3).
	FULL	6	F	Simulator is representative of X-22A except for gusts and ground effect, which are not considered to be well represented. Ratings apply to winds with gusts applied. Slight gusts with no wind in ground effect (RCR 5). Best representation of aircraft in ground effect was made with 5 kn head wind and gust level using ducts to trim head wind.
	FULL	5-6	G	Ground effect with low-level lateral gusts is representative of flight. Rapid descents can be performed easier than very slow descents, as found in flight. This effect probably due to a diminished gust response characteristic at reduced power. Rating given is with gusts without (RCR 3).
	FULL	7	H	Ground cushion was simulated approximately as in aircraft. Turbulence of low-level x-y gusts is approximate representation of aircraft IGE.
Flight	FULL	-	B	Rapid collective movement necessary to fly up through ground cushion. Movement required was considered not sensitive enough. Hover in ground effect feels like moderate turbulence. Very uncomfortable. Requires considerable pilot effort. Ground cushion strongly positive. Relatively rapid rate of descent required to descend through to touchdown is more than expected.
	FULL	4	C	Attitude upsets encountered IGE are moderate, stick activity is increased. Descent to touchdown pleasant compared to experience in other VTOL aircraft.
	FULL	5-6	D	Random shaking and buffeting experienced IGE up to wheel heights of about 10 ft. Strong, positive ground effect noted below 5 ft. Vertical landing task moving quickly through ground effect (RCR 4). Hover IGE and landing with 1/2 SAS rated RCR 9 since angular perturbations are noticeably larger than with FULL SAS and occurred with higher frequency.
	FULL	-	E	Lowering collective slowly increases ground effect exposure and chance of PIO. Roll-on landing technique decreases ground effect exposure time and reduces pilot effort required to land (RCR 3).
	FULL	5	F	Increased pilot work load. Ground effect turbulent and positive. Definite reduction in power required to descend last 5 ft.
	FULL	6-7	G	Developed PIO in vertical axis twice during hover (RCR 9), which was improved by releasing collective. Possibly some pitch down when descending into ground effect. IGE turbulence characterized by lateral shuffle. Strength of ground cushion is a surprise at first. Aircraft tends to stop descent at 10 to 20 feet. Apprehension due to turbulence also contributes to slow descent.
	FULL	7	H	Ground effect characterized by turbulence which masks the ground cushion effect to large extent. Control IGE is easier under moderate steady-wind conditions. (RCR 4 in steady 15-kn wind.) Slight negative ground effect occurs just above the ground cushion, which tends to produce a stable hover height at about 15 feet.

TABLE XXII. COMPILATION OF PILOT RATINGS AND COMMENTS FOR DYNAMIC FLIGHT TASKS IN HOVER

Case	Pilot	Height Dynamics	Pitch Dynamics	Roll Dynamics	Yaw Dynamics
BLFB	F	Slow thrust response.	Fast, similar to aircraft. No overshoot tendencies (RCR 3) with FULL SAS. RCR 4 with 1/2 SAS.	Response similar to aircraft but slightly more sensitive (RCR 3). Height control required with lateral translations.	Similar to aircraft.
ALMB	E	Almost identical to flight in vertical acceleration. Pitch attitude coupling is small amplitude. Simulation fidelity very good. Cues are similar to flight.	Pull and holds developed an acceleration which was more rapidly achieved than in flight. Pulse inputs felt more representative of flight.	Lateral response was initially similar to flight. Roll attitude travel limitation prevented evaluation of height coupling due to roll control.	Rudder response excellent. Identical to flight. Order-of-magnitude improvement over BHFB for control of yaw axis.
	F	Good response simulates flight pretty well. Time lag approximately 0.2 sec as in aircraft (RCR 3). With NO SAS and no gusts, RCR 5. With gusts, RCR 7-8.	No problem longitudinally. As the result of the input, an attitude is developed which is maintained as velocity builds up. Size of flight cube limits maneuver.	Slight amount of collective required to maintain height. Establishes bank angle in proportion to stick deflection.	-
	B	Collective not accompanied by coupling about other axes. No vertical damping noted. Vertical acceleration estimated 0.5 g/in.	Evident pitch damping; 1/4 in. input changes pitch attitudes with motion following the input. Appears to accelerate rearward more quickly.	Roll damping apparently less than pitch damping but still not degrading to pilot.	Appears to be pure rate system about this axis.
BHFB	F	-	Essentially deadbeat response to pitch.	Essentially deadbeat response to aileron pulses.	Essentially deadbeat response to rudder pulse.
Flight	B	-	Aircraft quite stable in pitch and roll. Feels like attitude control system with high frequency and low damping.	-	-
	D	Negative ground effect sensed at about 20 feet produced downward acceleration. Positive ground effect noted at 8-10 feet. Height oscillation developed between 5-10 feet. This negative to positive gradient is undesirable and gives PIO tendency on landing (RCR 5).	Initial response to forward input is nose down and height loss. Attitude then stabilizes, nose pitches up to peak, and height increases. Period is approximately 8 sec, damping near neutral. Much faster initial response with 1/2 SAS, which is similar to NO SAS operation in BHFB (RCR 6). A long-period longitudinal oscillation excited by beeping the ducts appeared to have a 1-cps neutrally damped secondary oscillation superimposed.	Initial response to lateral push and hold is rapid roll to a bank angle which decreases as the speed builds up. Moderate height loss was noted in contrast to a gain for pitch. Mild adverse yaw but no yaw with lateral velocity. With 1/2 SAS response is noticeably faster (RCR 6).	Yaw rate response to small steps. Control sensitivity and damping satisfactory (RCR 2). Larger step input (1 in.) gives acceleration response (RCR 4). Mild loss of height noted (RCR 3). With 1/2 SAS, an acceleration response resulted from a 1 in. step (RCR 5).
	E	Slow response with minimum physical vertical acceleration cues which were most noticeable in descent. Engine transients barely audible. No bothersome control coupling noted.	-	-	Right pedal gives right yaw. Initial acceleration decreases quickly to steady turn rates. Acceleration is proportional to input. Translation develops as turn progresses out of wind.
	F	Good thrust response. No noticeable attitude coupling.	Pitch attitude response very fast. No tendency to PIO. 1/2 SAS barely noticeable.	Roll attitude response very fast. Lateral translation requires slight increase in collective.	Rudder response quick. Develops yaw rate. Easy to start and stop. Yaw easier to control with NO SAS than pitch or roll.
	G	-	Very fast response (RCR 3) with no overshoot (RCR 2), but feels like it might PIO if moved too fast (objectionable).	-	-

TABLE XXIII. COMPILATION OF PILOT RATINGS AND COMMENTS FOR STEADY FLIGHT TASKS AT FIXED OPERATING POINTS IN TRANSITION

Task	Case	RCR	Pilot	Comments
Longitudinal Trim and Static Stability	BLFB	3	F	Slightly more stable at $\lambda = 60^\circ$ (RCR 3) than at 30° (RCR 3.5). Control activity normal. Control forces representative. More sensitive in pitch and roll and slight tendency to PIO in roll at 30°
		3	H	Roll and yaw activity high, pitch normal. Similar to aircraft.
	ALMB	-	F	Neutral to slightly negative stability. Resembles flight. Occasional lateral oscillation.
	BHFB	-	D	Difficult to trim and hold altitude at $\lambda = 30^\circ$. Stability in trim seemed to be stable; not representative.
		-	B	Stability hard to tell from pitch forces at $\lambda = 0^\circ$. Seems to be a nosedown drift in pitch trim.
	FLIGHT	2.5	B	Difficult to trim. Static stability at $\lambda = 60^\circ$ seemed neutral (RCR 3). Stability seems to vary slightly with angle of attack. Near-neutral stick-position stability at $\lambda = 0^\circ$ indicated by small forces required to change speed (RCR 2).
		4.5	D	Static stability at $\lambda = 45^\circ$, 30°, and 0° is neutral to mildly negative (RCR 4, VFR; RCR 6, IFR). Acceptable for VSS research vehicle.
		5	E	Ability to hold specific trim point is difficult. Static stability neutral to negative.
		3	F	Neutral to negative static stability. Difficult to trim.
Static Directional Stability	BLFB	3	F	Maximum sideslip limited by simulator scaling; otherwise representative of flight. Positive static stability.
	ALMB	5	F	Positive static stability but not as good a simulation as BLFB due to instrumentation and computer difficulties. Lateral-directional control forces generally representative.
	BHFB	3	B	Positive static stability. Maximum sideslip at approximately 8°. Poor simulation primarily due to yaw trim drift and inadequate yaw displays.
	FLIGHT	4	B	Statically stable at $\lambda = 0^\circ$. Positive dihedral. Low stability at small sideslip angles at $\lambda = 60^\circ$.
		4	C	Low directional stability at $\lambda = 45^\circ$.
			D	Difficult to hold small sideslip angles at $\lambda = 0^\circ$ and 30°. Neutrally stable for $\pm 2^\circ$; stable at higher sideslip angles. Steady sideslip made to $10\text{-}1/2^\circ$ at $\lambda = 45^\circ$. Slight duct buzz above 5° sideslip. Noseup pitching moment with sideslip noted.
			E	Neutrally stable at small angles of sideslip to $\pm 2\text{-}1/2^\circ$. Stable above.
		3	F	
Banked Turns	BLFB	3	F	Response to control inputs is normal to fast and compares well with flight. Slight to mild tendencies to overshoot and PIO roll are noted at $\lambda = 30^\circ$; control forces and motions comparable.
		3	H	More difficult to perform at bank angles greater than 20° (due to limitation in simulator scaling).
	ALMB	3	F	Task performed in 100:1 motion scaling similar to aircraft. IFR indicates motion due to roll control approximately as in aircraft. Attitudes representative, but g's do not feel right.
	BHFB	-	D	Generally good representation of aircraft. Response to roll-in seems about right. Statics do not seem right. Flight requires more rudder. Tendency to sit at about 2° sideslip is same as aircraft.
	FLIGHT	4	B	Greater effort required to coordinate turns than usual for conventional aircraft. Turns entered with stick only exhibit initial adverse sideslip which changes and becomes favorable as turn progresses.
		4	C	Rudder forces too high for stick at $\lambda = 30^\circ$. Turns easier at $\lambda = 60^\circ$ (RCR 3).
		3	D	Rudder required is proportional to bank angle. Smooth turn entries and recoveries obtained by leading lateral control with rudder. No side force cue as to amount of rudder required.
		4	E	Rating given overall.

TABLE XXIV. COMPILATION OF PILOT RATINGS AND COMMENTS FOR DYNAMIC FLIGHT TASKS AT FIXED OPERATING POINTS IN TRANSITION

Task	Case	RCR	Pilot	Comment
Long-Period Longitudinal Dynamic Mode	BLFB	4	F	Nonoscillatory divergent motion at $\lambda = 30°$. Slightly divergent noseup and down ($\lambda = 0°$).
		3	F	Nonoscillatory neutral at $\lambda = 60°$.
	ALMB	5	F	Nonoscillatory slightly divergent and underdamped motion at $\lambda = 30°$. Resemble flight.
	BHFB	4	C	Nonoscillatory divergent motion at $\lambda = 30°$.
		6	D	Slowly divergent from trim both noseup and nosedown at $\lambda = 30°$. Quality of simulation rated fair. Long-term dynamics vary with duct angle as they do in the airplane.
		5	B	Slow to diverge at $\lambda = 0°$.
	FLIGHT	3	B	Motion was nonoscillatory divergent at $\lambda = 0°$ with recovery initiated after ~~26-sec~~ nose-down and 50-sec noseup for an equal change in pitch attitude.
		2	C	Neutral with hands-off in trim at $\lambda = 60°$.
		4	D	Mildly divergent from trim both noseup and nosedown at $\lambda = 30$ (RCR 4). Faster divergence at $\lambda = 0°$ (RCR 6) possibly due to more out-of-trim condition.
		-	E	Motion appears to be divergent at $\lambda = 15°$.
			F	
Short-Period Longitudinal Dynamic Mode (Sharp pulse-type pitch input)	BLFB	3	F	Nonoscillatory convergent well damped at $\lambda = 30°$.
	ALMB	3	F	Nonoscillatory convergent well damped at $\lambda = 30°$.
	BHFB	3	B	Well-damped short period at $\lambda = 0°$. Only apparent motion is long-term divergence.
		4	D	Nonoscillatory convergent at $\lambda = 30°$. Quality of simulation rated poor.
	FLIGHT	2	B	Heavily damped in 1/4 to 3/4 cycle at $\lambda = 0°$. Nonoscillatory overdamped at $\lambda = 60°$. At the most, there is maybe one overshoot.
		3	D	Nonoscillatory convergent at $\lambda = 30°$ and $0°$. Did not particularly like it, probably because of the high sensitivity.
		-	E	Oscillatory convergent well damped at $\lambda = 30°$.
			F	Essentially deadbeat.
		2	H	Deadbeat at $\lambda = 30°$.
Lateral-Directional Dynamic Mode	BLFB	3	F	Nonoscillatory convergent well damped at $\lambda = 0°$, $30°$, and $60°$.
	BHFB	-	D	Two techniques used to excite motion. Quality of simulation judged to be fair for release from steady sideslip, and good for rudder walk technique.
	FLIGHT	-	E	At $\lambda = 15°$, $22°$ motion is damped oscillation with a period of approximately 5 sec. Lateral-directional mode easily excited by walking rudders.
		5	D	Directional mode as excited by release from steady sideslips and rudder walking was quickly damped. Persistent lateral oscillation with approximately an 8-sec period present at $\lambda = 30°$, but not at $0°$. No coupled motion noted at $0°$ (RCR 2). Oscillation moderately damped at duct angle $45°$. Crosscoupled spike seems to be the best test technique.
		3	B	Motion appears to be oscillatory at $0°$ duct angle and damps in approximately 1-3/4 cycles.
		4	F	Directional oscillation is damped (RCR 3). Lateral oscillation persists at small amplitude (RCR 5).
		3	H	At $\lambda = 30°$, flight control not difficult; rudder kicks performed while maintaining bank angle within $\pm 10°$.

TABLE XXV. COMPILATION OF PILOT RATINGS AND COMMENTS FOR CONTINUOUS CONVERSIONS AND RECONVERSIONS

Case	RCR	Pilot	Comment
BHFB	4	B	Ducts were rotated down intermittently in intervals of approximately 1 sec with fuselage attitude held level. Large height variation and excessive pitch trim changes experienced. Lateral control motion was high. Heading hold difficult due to display. Rapid steady-rate conversions were difficult to stabilize. Overall control performance rating for conversions was below average (RCR [illegible]). Pilot work load in transition was rated high. Ability to initiate and terminate conversions and reconversions was rated average, and control responses during these tasks were normal (RCR 3).
	4	C	Several conversions and reconversions were made using duct rotation both intermittently and at maximum continuous rate (RCR 4). Collective stick and thrust rotation rated (RCR 2-3). Pitch trim too slow (RCR 5). Yaw control rated RCR 4, probably due to presentation which was not considered to be good for IFR. Either roll response seemed to be slow or lateral stick force was high (RCR 4), but roll control was O.K. (RCR 2). Pilot work load rated high (RCR 4-5).
	7.5	D	Initially during reconversion, thrust control is used essentially as a height control; subsequently as a speed control. The crossover point in use of thrust control is hard to judge (RCR 7) because height cues are poor (RCR 6). Pitch stick was used to keep fuselage attitude level. Pitching moment required was considered to be too high and pitch control rated RCR 6. Roll control required too much effort; roll sensitivity and damping rated poor (RCR 7). Yaw control used to hold course (RCR 5). Overall work load for reconversion rated excessive.
	-	E	Conversion and reconversion trim and attitude changes provided reasonable indications and cues.
	3-4	F	Use of collective to maintain altitude more difficult during reconversion. Thrust rotation at pilot's discretion. Pitch attitude difficult between $\lambda = 0^\circ$ and 30° due to large trim change. Roll and yaw control O.K. Conversion, RCR 3; reconversion, RCR 4.
Flight	-	B	Conversion from $\lambda = 90^\circ$ to 30° made with fuselage level. The sense of horizontal acceleration was surprising, as normal pilot tendency is to lower the nose to gain speed as learned in helicopter training. Duct rotation switch on collective stick is good. On rotation from $\lambda = 30^\circ$ to 0°, the fuselage attitude had to be increased, which complicated the pilot task. The conversion was rated difficult. For reconversion, ducts were rotated from $\lambda = 0^\circ$ to $\lambda = 45^\circ$. Speed response to duct rotation was immediate. Rapid noseup trim change requires nosedown control. Reduced collective necessary to prevent climb. As ducts rotated further to 90° aircraft stability increased in pitch and roll.
	-	C	Acceleration rapid and comfortable in fast conversion to $\lambda = 20^\circ$. Further conversion resulted in strong requirement for full-up collective and nose-up attitude which was not sufficient to level off at 130 kn and $\lambda = 0^\circ$. Fast reconversion at constant collective results in rapid climb (RCR 4). Reduced collective is required. Reconversion from $\lambda = 30^\circ$ to 90° more manageable. Increased collective at $\lambda = 90^\circ$ obvious and easily accomplished (RCR 3).
	3-4	D	In conversions, a significant reduction in power is required at about $\lambda = 60^\circ$. Strong noseup pitch change noted and rated excessive (RCR 5) because retrim effort is added to already high work load. Duct buzz evident between $\lambda = 70^\circ$ and 50°. Height controlled without difficulty (RCR 3). Maximum rate conversion easier to perform. Overall rating for fast conversion, RCR 3; for slow, RCR 4. In level reconversions, considerable difficulty experienced between $\lambda = 0^\circ$ and 30° in holding pitch attitude, partly due to lack of good visual attitude cue and partly due to trim change. Changeover from using collective for speed control to collective for height control was difficult to phase. Judgment of closure rate and deceleration to stop at selected spot was difficult. Reconversion not rated overall.
	3-5	E	In both slow and rapid conversions, initial noseup trim change noted between $\lambda = 90^\circ$ and 70°. Essentially no large pitch changes noted between $\lambda = 70^\circ$ and 30°. Further rotation to $\lambda = 15^\circ$ results in significant nosedown trim change, requiring attitude trimming. Between $\lambda = 15^\circ$ and 0°, there is a continuous requirement for up collective and aft retrimming, and a lateral PIO tendency was noted during slow conversions. In reconverting, an initial ballooning (climb tendency) noted with duct rotation causes high work load, which decreases again until ducts near 90°. Work load increases again in hover. Rapid conversions and reconversions are easier to perform because pilot cues are more apparent (RCR 3). Slow (RCR 5). Descending reconversion with slow duct rotation and aircraft altitude monitoring easily performed (RCR 3). Work load rated low compared to level maneuver. Trim changes obvious but not objectionable.
	3	G	Conversion performed from stabilized hover by beeping ducts to $\lambda = 70^\circ$ and rotating continuously thereafter. Collective used to control height and stick for fuselage attitude for level conversion; nose rotated up and collective added from about 100 kn (i.e., between $\lambda = 15^\circ$ and 0°). Conversion easily accomplished (RCR 3). Pilot work load rated average. Forward stick required in early stage of conversion is undesirable for IFR. This characteristic is typical of helicopters, but their stick requirement does not reverse as speed increases. Rolling turn during conversion improves visibility and makes maneuver acceptable. No lateral handling problem noted, even though conversions were made in 90° crosswind.
	4	G	Reconversion predictable and repeatable using moderate beeping of ducts initially from stabilized flight at 120 kn, $\lambda = 0^\circ$, and continuous duct rotation on approaching hover point. Large and rapid application of thrust required when entering hover. Difficult to tell position of ducts when concentrating on landing target. Reconversion is similar to helicopter "quick-stop" maneuver but without high noseup attitude.
	3	H	Conversion from hover to $\lambda = 30^\circ$ is RCR 2; it is RCR 4 from $\lambda = 30^\circ$ to 0° due to larger trim and power changes. Reconversion from $\lambda = 30^\circ$ to hover, RCR 3.

APPENDIX III
CORRELATIONS OF SIMULATOR STATIC AND DYNAMIC RESPONSE CHARACTERISTICS WITH FLIGHT

In order for an aircraft to be adequately simulated, the individual aerodynamic and control system parameters must be represented to a tolerance within the threshold of pilot sensitivity; that is, his ability to detect a difference. Although this degree of accuracy in the representation of stability and control parameters is a necessary condition, it is not a sufficient one, since there are many other elements of the simulation that can cause the handling qualities to be misrepresented. Most of these other elements have been discussed elsewhere in this report, and this appendix presents comparisons and evaluations of the simulated static and dynamic stability and control characteristics with flight as an indication of the degree of fidelity of the different simulations.

Data presented were taken from the recorded time histories of significant flight parameters and include examples of control position and attitude stability and trim in hover and transition, the trend of control position with velocity in continuous transitions, and time histories of dynamic motions and responses to control inputs in hover and at fixed operating points in transition.

STATIC STABILITY AND CONTROL CHARACTERISTICS

This section presents comparisons of the static stability characteristics of the different simulators with flight. Results show that the fixed operating point static derivatives are reasonably representative of flight for all simulators. An exception is the value of L_V, used in the BLFB and ALMB simulations, at $\lambda = 30°$, 80 kn, which slightly exceeded the usual range of pilot tolerance to this parameter; however, the fact that this difference went undetected, by the pilots, indicates that these simulations were also adequate.

Fixed Operating Points

Static characteristics are best compared by plotting stick position and physical attitude as a function of velocity. Differences between equivalent cases are evaluated by solving and comparing the static equations of motion in the steady state, and relating differences in simulated flight characteristics to the pilot judgments of flying qualities as interpreted from the pilot comments received.

Hover

The static longitudinal parameters of pitch attitude θ and stick position δ_{PS} are presented in Figure 9, as a function of velocity. Simulator and flight data appear to be in reasonable agreement; an evaluation of the longitudinal equations

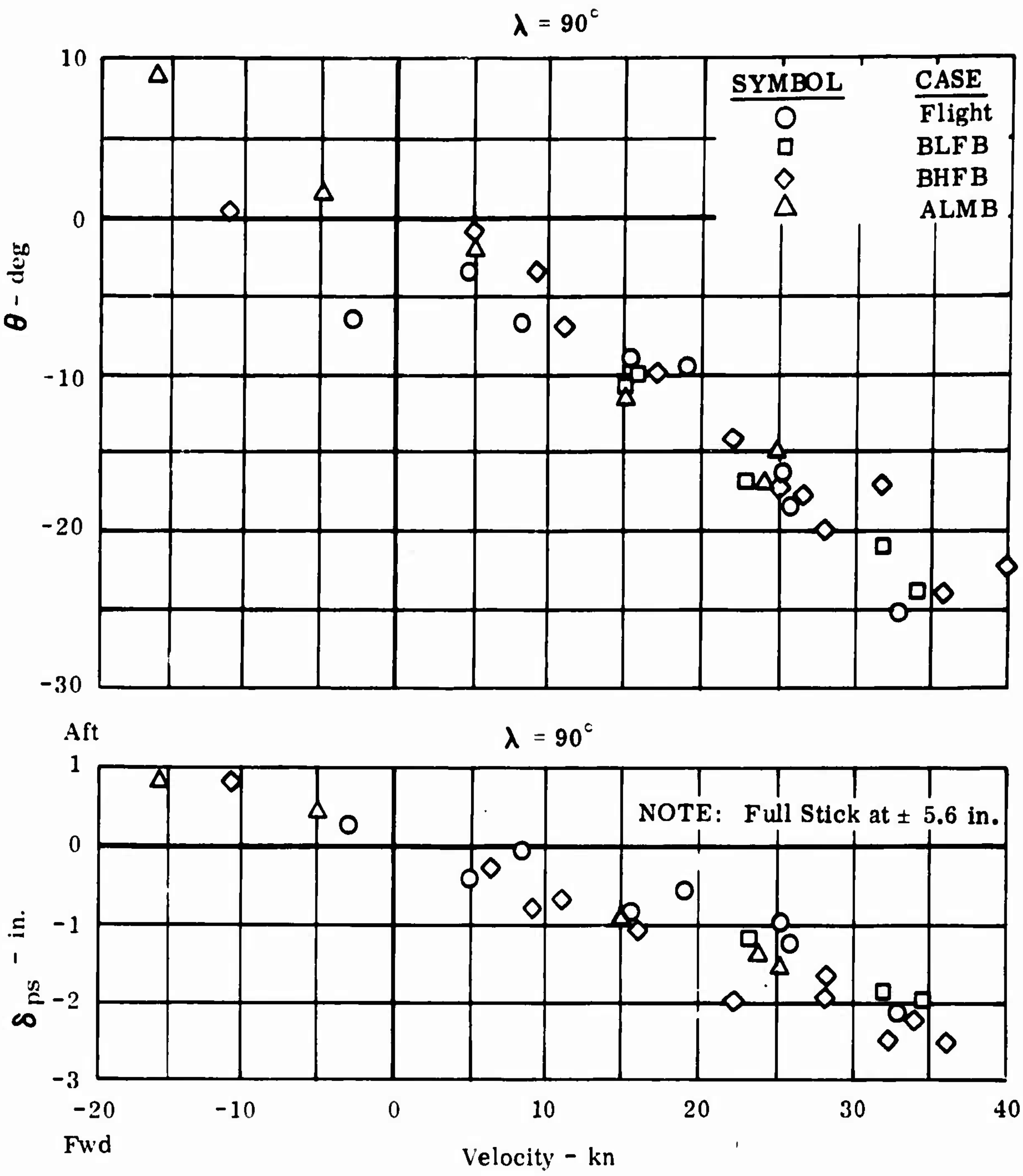

Figure 9. Comparison of Pitch Attitude and Stick-Position Stability in Hover for Simulators and Flight.

of motion for steady forward flight indicates that the individual terms are adequately represented.

The longitudinal force and moment equations in steady forward flight are

$$X_u u + X_w w + W \sin\theta = 0 \tag{109}$$

$$Z_u u + Z_w w + \left[1 - \frac{T}{W}\right] W \cos\theta = 0 \tag{110}$$

$$M_u u + M_w w + M_{\delta_{ps}} \delta ps = 0 \tag{111}$$

Because height damping in the X-22A is low and pilot comments show that there is virtually no pitch attitude coupling with height control, the height equation (110) is uncoupled from the longitudinal equation (109) and the pitching moment equation (111) and can therefore be neglected in evaluating Figure 9. Therefore, pitch attitude can be obtained directly from equation (109) and is given simply by

$$\theta = \sin^{-1}\left(\frac{-X_u u - X_w w}{W}\right) \tag{112}$$

Since, at very low speeds, the X_w term in the X-22A is zero, this equation further reduces to

$$\theta = \sin^{-1}\left(\frac{-X_u u}{W}\right) \tag{113}$$

By substituting corresponding experimental values of u and θ into equation (113), the value of the X_u term used in the simulation programs can be shown to be reasonably correct. In the same manner, since M_w in the X-22A is zero in hover, equation (111) can be evaluated to show that the simulated values of $M_{\delta_{ps}}$ and M_u are reasonable representations of flight.

Static lateral parameters of bank angle ϕ, and roll stick position δ_{rs}, from the different simulation programs, are compared with flight results in Figure 10, as a function of lateral velocity. These results can be evaluated in terms of the lateral force and moment equations which, in hover, are essentially independent.

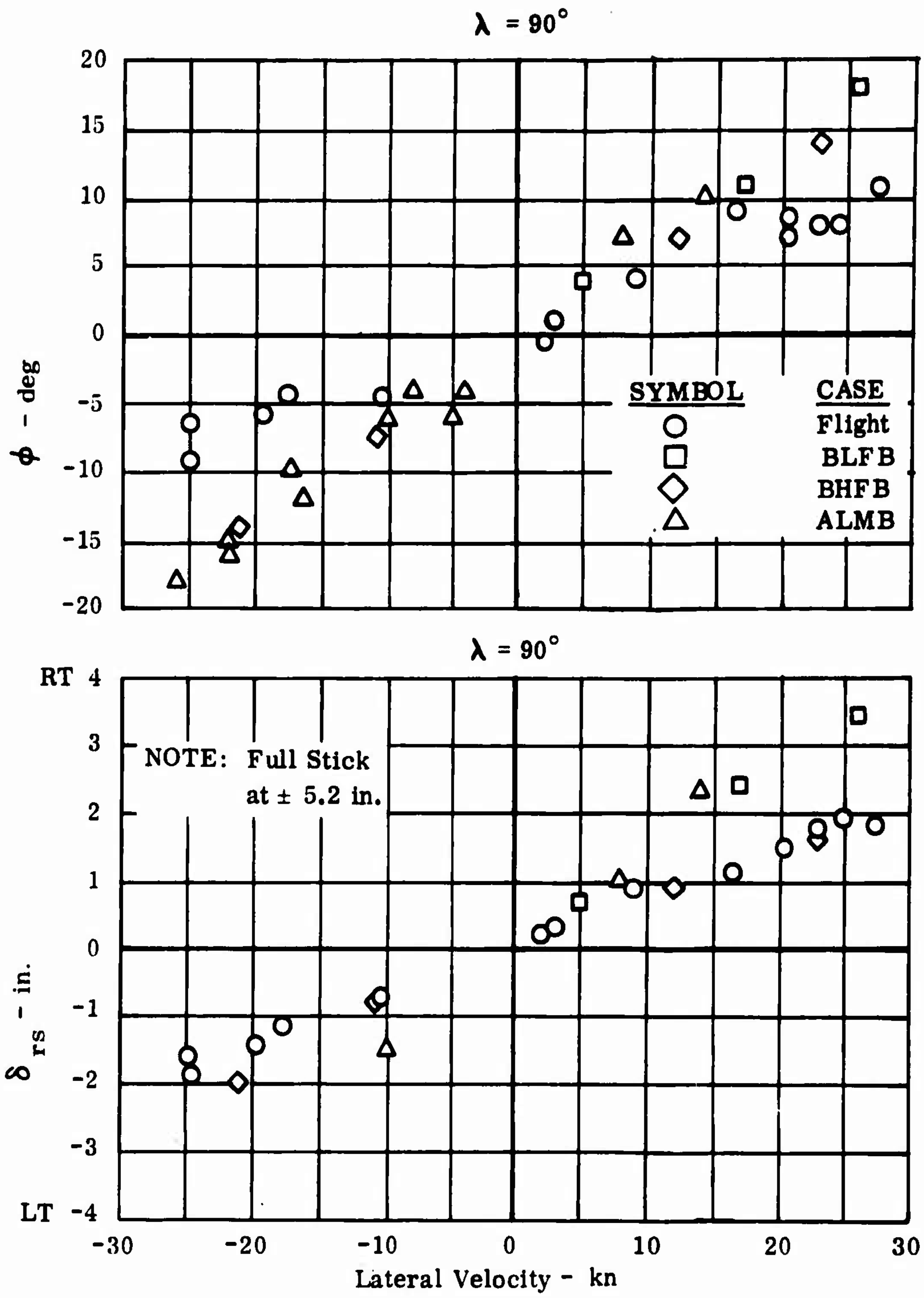

Figure 10. Comparison of Roll Attitude and Stick-Position Stability in Hover for Simulators and Flight.

The steady-state lateral equations are simply

$$Y_v v + W \sin \phi = 0 \tag{114}$$

$$L_v v + L_{\delta_{rs}} \delta_{rs} = 0 \tag{115}$$

$$N_v v + N_{\delta_a} \delta_a = 0 \tag{116}$$

From the side force equation (114), the bank angle can be expressed as

$$\phi = \sin^{-1} \frac{Y_v v}{W} \tag{117}$$

In Figure 10, the experimental trends and levels of bank angle with lateral speed from all simulations are shown to be in reasonable agreement with flight. Substitution of corresponding values of speed and bank angle in equation (117) indicates that the Y_v term is adequately represented.

From the rolling moment equation (115), lateral stick position can be expressed in terms of the ratio of $L_v/L_{\delta_{rs}}$

$$\delta_{rs} = \frac{L_v v}{L_{\delta_{rs}}} \tag{118}$$

Experimental data for lateral stick position from the BHFB are in reasonable agreement with flight, but results from the BHFB differ appreciably. Since control power levels were the same in all simulations, this difference is attributed to an inadvertent misrepresentation of L_v in the BLFB and ALMB simulations, which used a value of -0.056 (rad/sec^2)/(ft/sec) instead of -0.0394, as quoted in Reference 12 (which gives a much closer representation of the experimental flight results). It is interesting to note that the pilots were apparently insensitive to this difference since they did not detect and comment on the different characteristics. The expression for pilot tolerance to L_v from page 93 of Reference 12,

$$\Delta L_v = \pm \left[0.6 + 6(L_{v_o})\right] \left|L_{v_o}\right| \qquad (\mathrm{rad/sec^2})/(\mathrm{ft/sec}) \tag{119}$$

defines the threshold of pilot sensitivity about L_v = 0.0394 as the range of values from -0.025 to -0.054 (rad/sec^2)/ ft/sec). Since the value of -0.056 used in the BLFB and ALMB program is only slightly beyond this range and since the effects of the difference were undetected, the representation of L_v as performed is considered to be adequate.

Transition, $\lambda = 30°$

The stick position required for equilibrium level flight at various trim speeds and the stick-position stability within ±15 kn from trim are presented in Figure 11. The simulation results were obtained from the BHFB simulation and show very good agreement with flight for trim speeds of 90 and 120 kn. The gradient of the stick position with respect to speed for the 80-kn trim evaluation is greater for simulation than it is for flight. However, the gradient has the proper sign, which is important in evaluating stability. The maximum error in stick position of 1/2 inch was probably imperceptible, because pilot comments indicated that the simulator was much like the aircraft.

The lateral-directional static stability parameters of δ_{rs}, δ_{rp}, and ϕ are presented in Figure 12 as a function of sideslip angle. These data show generally good agreement with flight for the BHFB and BLFB.

Continuous Conversion and Reconversion

Continuous transitions at constant altitude can be made for an infinite variety of combinations of the independent variables, which include λ, θ, δ_{ps}, δT_c, and V, so that there is no unique correspondence of parameters, and quantitative comparisons of several continuous transitions are difficult to make. Figure 13 presents a comparison of several conversions and reconversions performed in both the aircraft and the simulator. The characteristic forward stick position to maintain an equilibrium speed in midtransition is clearly shown. While none of the simulated transitions have an exact counterpart in flight, they all exhibit similar trends, and the range of variation amoung the various parameters is approximately the same in the BHFB as it is in flight.

DYNAMIC STABILITY CHARACTERISTICS ANALYSIS

This section presents comparisons of the dynamic response time history records of important parameters for the different simulators with flight. Results show that the aircraft dynamics were reasonably well represented in all simulators, and that the extent of the differences shown by the data was for the most part within the scatter of the pilot ratings and comments received.

Variation of Stick Position with Speed
Pitch Control Mode

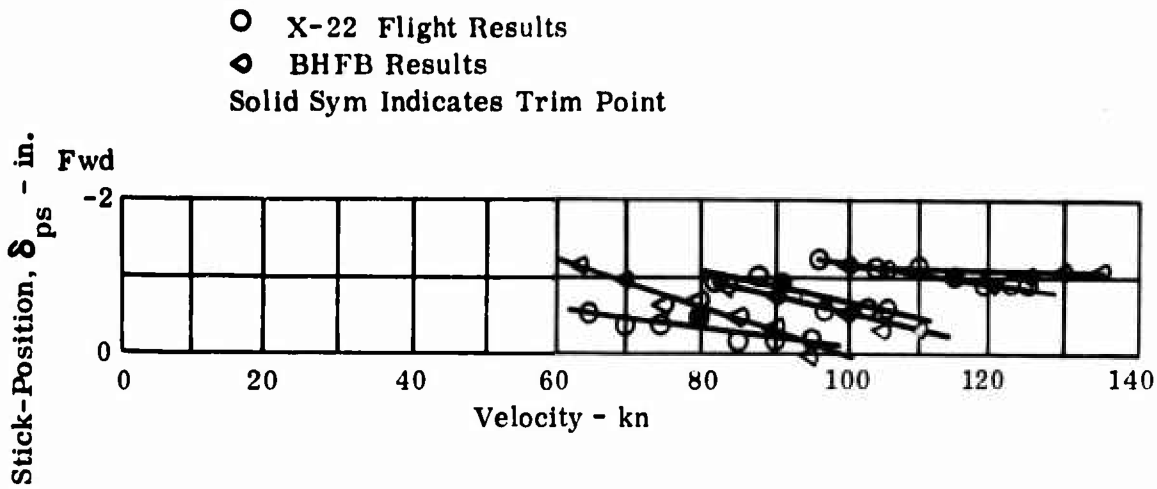

Figure 11. Comparison of Pitch Stick-Position Stability in Fixed Operating Point Transition (λ = 30°) for Simulators and Flight.

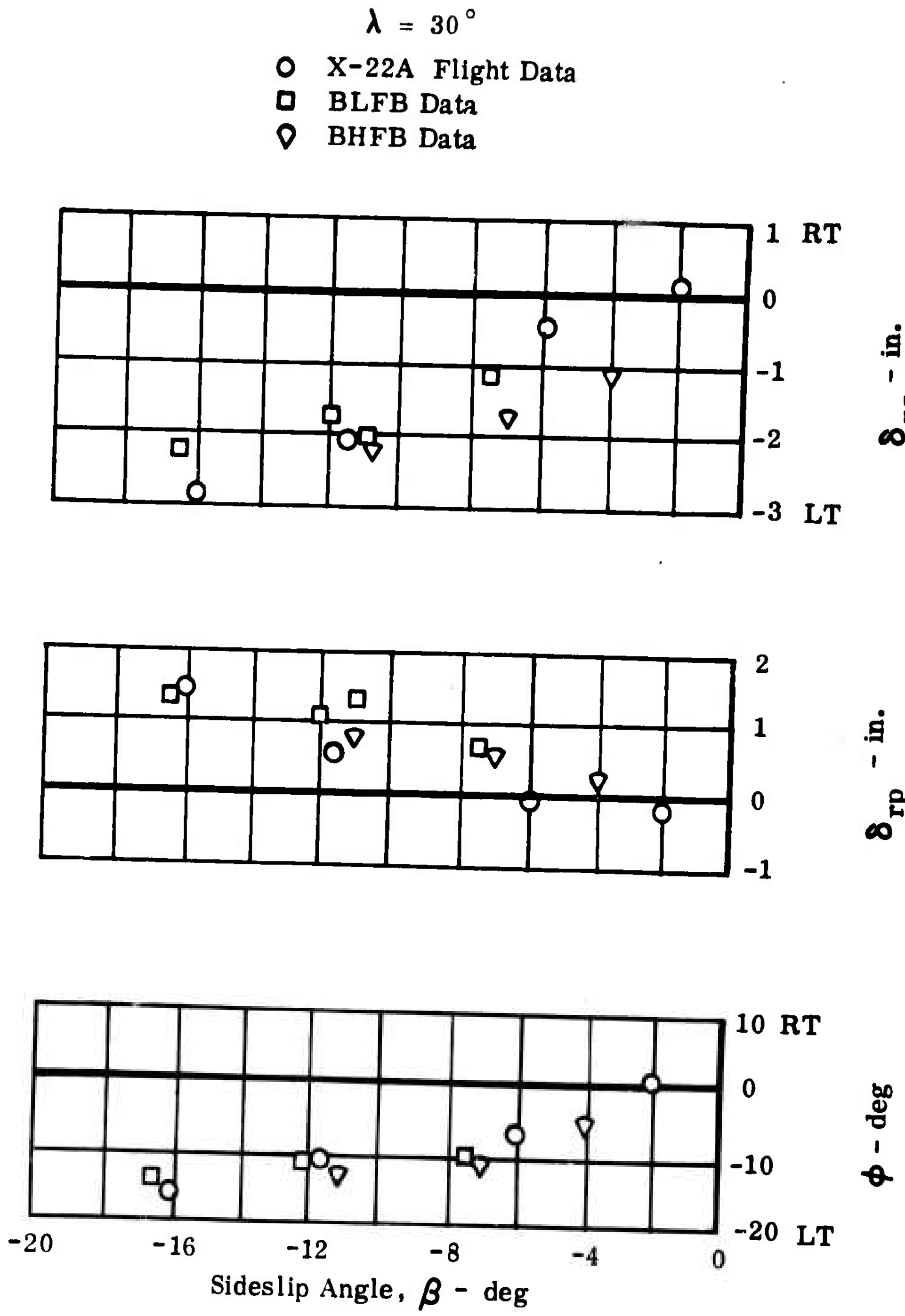

Figure 12. Comparison of Roll Attitude Stability and Roll Stick and Rudder Pedal Position Stability in Fixed Operating Point Transition for Simulators and Flight.

Note: F - Flight
S - Simulator
C - Conversion
R - Reconversion

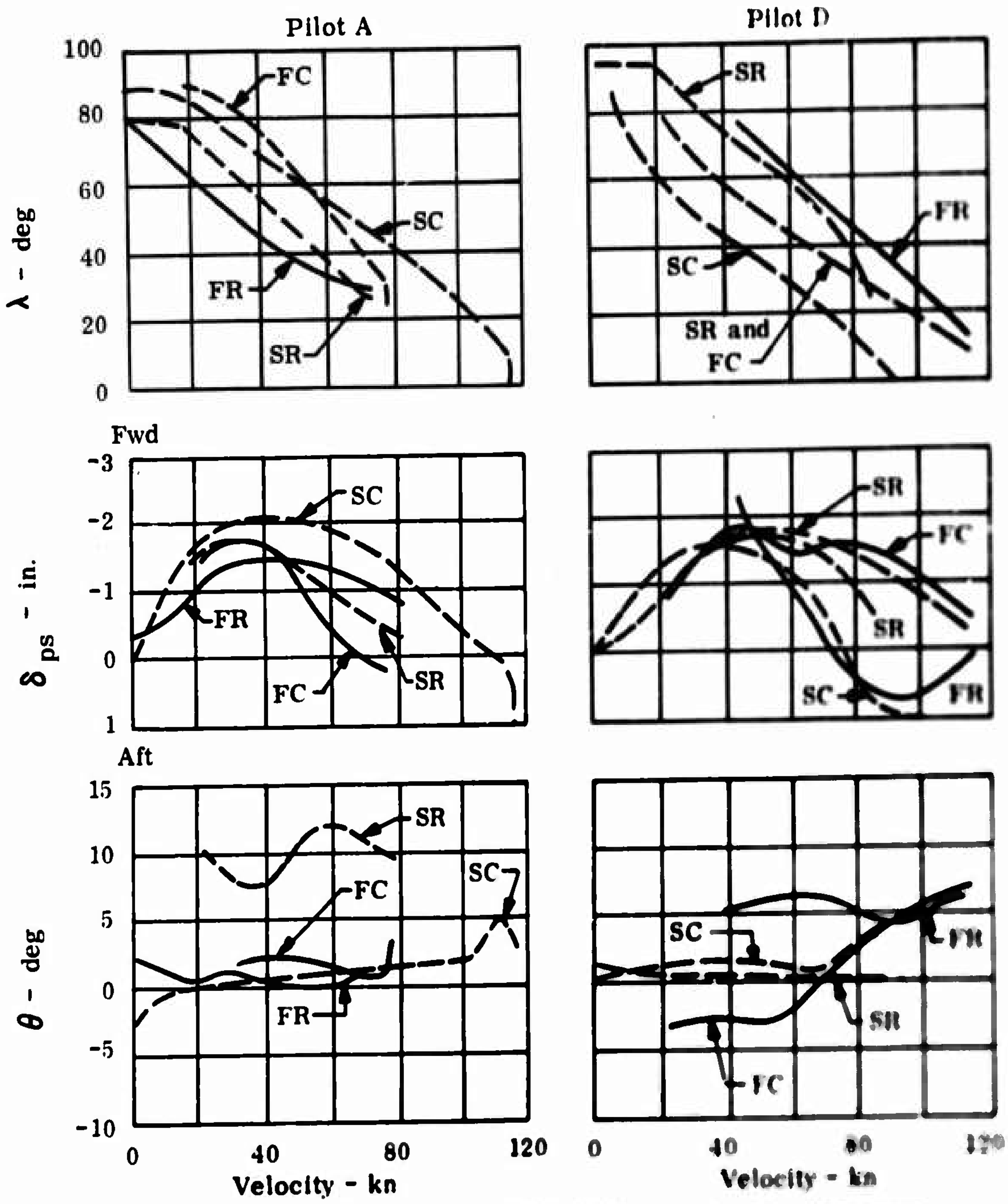

Figure 13. Comparison of Flight Parameters in Continuous Transition for Simulators and Flight.

Comparisons in hover are presented for dynamic characteristics in pitch, roll, yaw, and height. Comparisons at fixed operating points in transition are given for the inherent longitudinal and lateral-directional dynamic responses, and for the short-period responses to pitch and roll control inputs.

Height Dynamics In Hover

Responses of the different simulators to step inputs of the collective stick are compared with flight results in Figure 14. Height control inputs are shown to command an acceleration response in all simulations as in flight. Typically, the response to the input is a relatively undamped acceleration, which can be stopped only by a corresponding input in the opposite direction. The inherent height damping of the X-22A is very low, and since there is no augmentation in this axis, the pilot must provide his own damping by anticipating the response with the collective stick. In rough air and in ground effect where the vertical mode is continually excited, these control characteristics are quite sensitive to pilot-induced oscillations. In the opinion of all pilots, the height control mode as simulated was representative of flight.

Pitch Dynamics In Hover

Responses of the different simulators to pulse-type pitch stick inputs in hover are compared with flight results in Figure 15. Results in all simulators are shown to be very similar to flight. The delay in pitch attitude response appears to be less than 1/4 sec in all cases, and pitch rate returns promptly to zero with negligible overshoot. The residual pitch rate oscillation evident in the flight results was caused by pitch stick inputs during the recovery maneuver.

Responses to step inputs in pitch for the different simulators in hover are compared with flight results in Figure 16. The response in the BLFB agrees very closely with the flight response. The difference seems to be in the rate with which pitch rate returns to zero. From comparable initial pitch, the pitch rates and the BLFB returned to zero in 6 sec, whereas the aircraft returned in 3-1/2. This difference may be the result of external disturbances such as gust effects in the flight results or a difference between the simulated and the true aerodynamic damping. In the ALMB, the longest available step input was sustained for approximately 2 sec, which is not time enough for the full oscillation to develop. However, longer steps could not be sustained without exceeding the limits of the flight cube. Comparable data from the BHFB simulation were not available. Pilot comments for longitudinal dynamic response in hover indicate that all simulations were well representative of the aircraft.

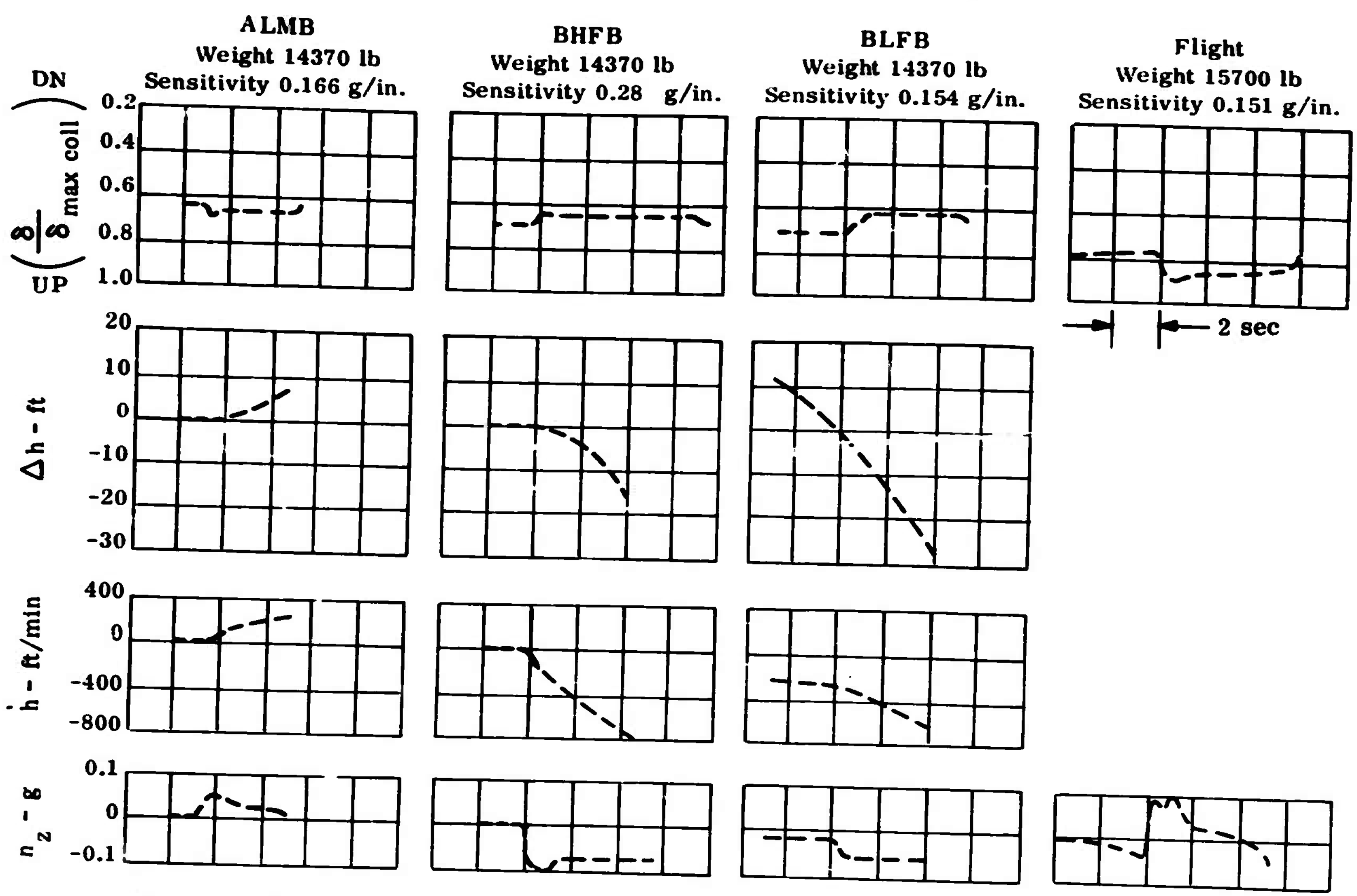

Figure 14. Comparison of Dynamic Response to a Step-Type Input of the Collective Stick in Hover for Simulators and Flight.

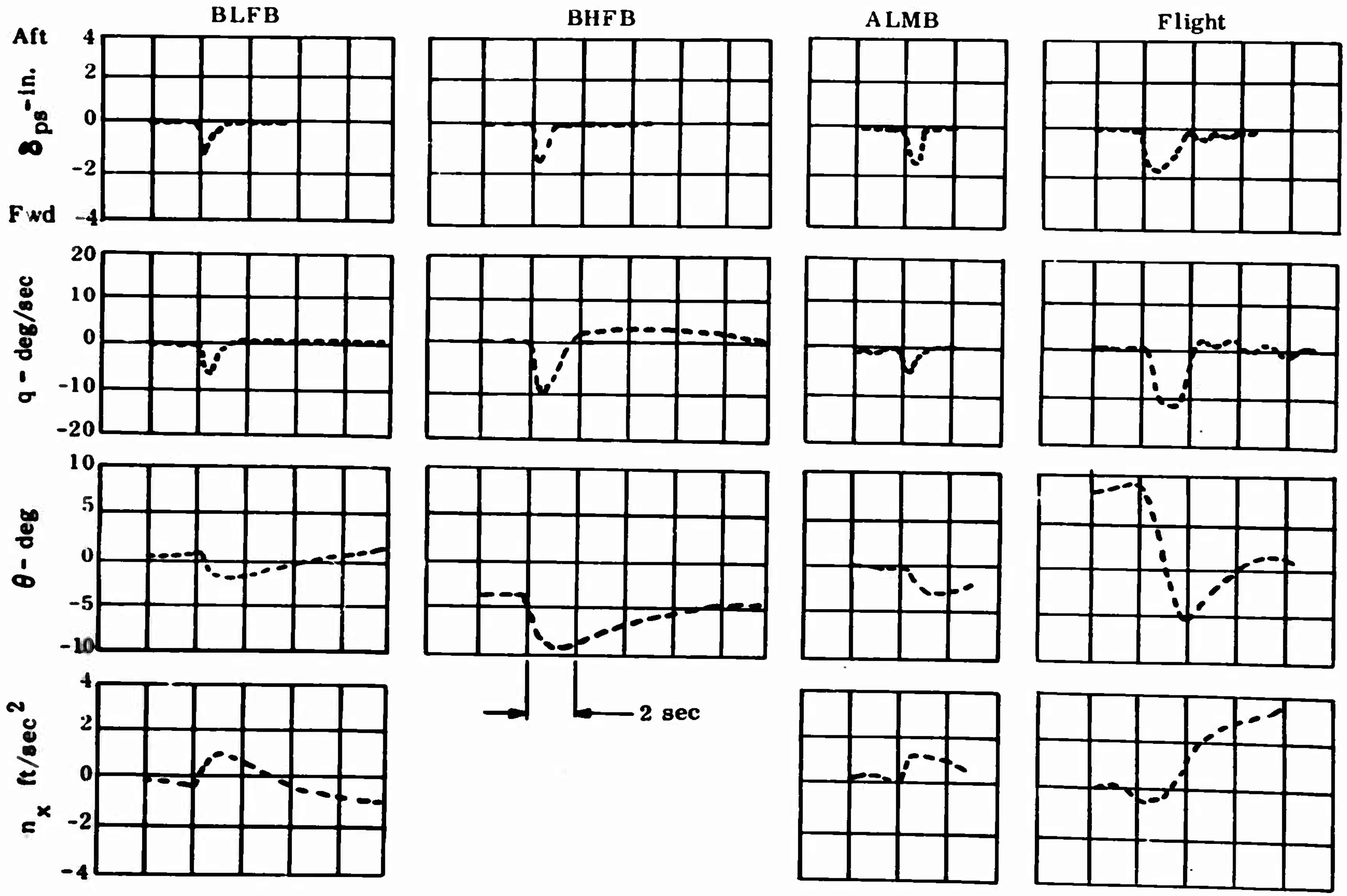

Figure 15. Comparison of Dynamic Response to a Pulse-Type Input of the Pitch Control in Hover for Simulators and Flight.

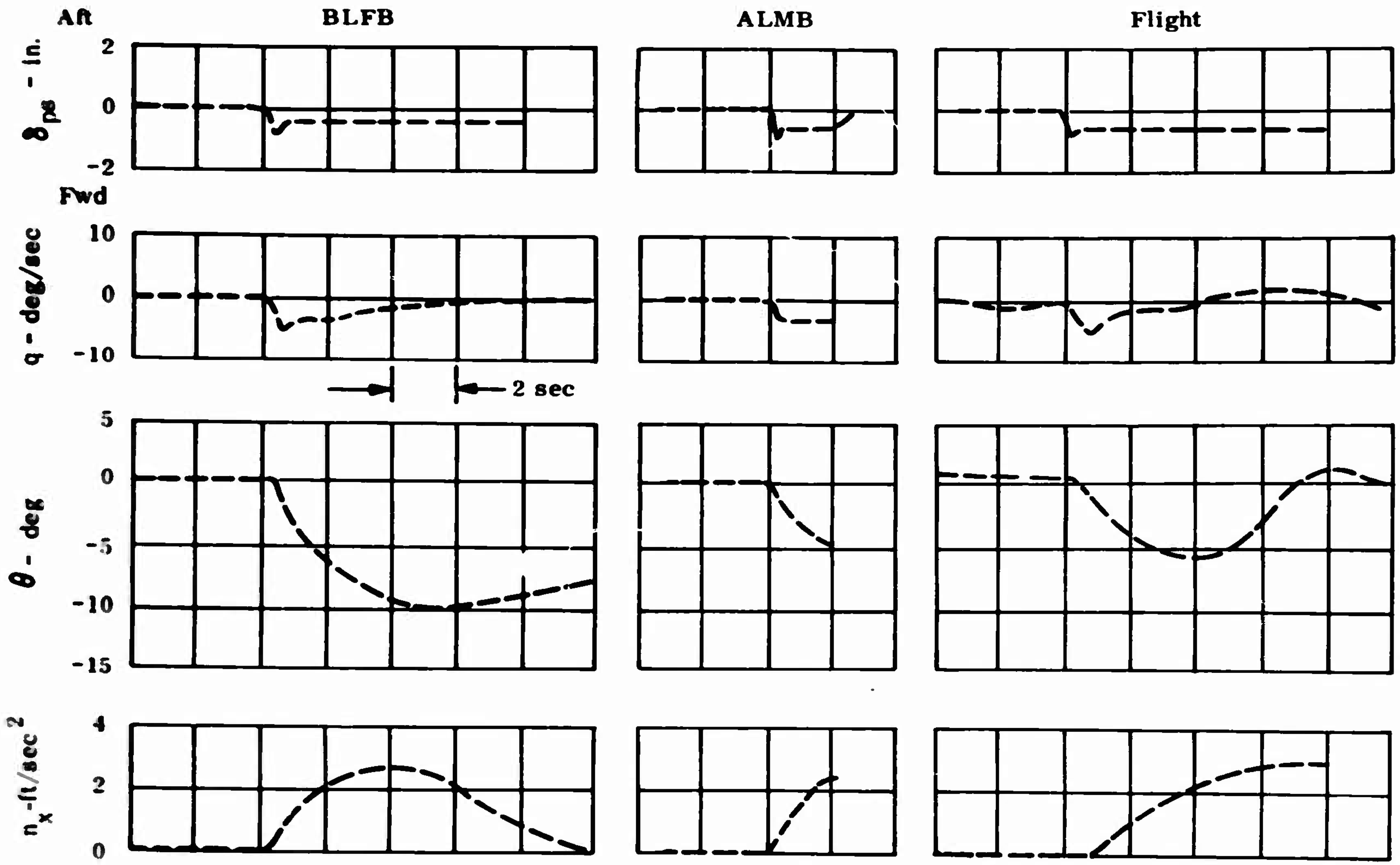

Figure 16. Comparison of Dynamic Response to a Step-Type Input of the Pitch Control in Hover for Simulators and Flight.

Roll Dynamics In Hover

Responses to pulse-type roll stick inputs for the different simulators in hover are compared with flight results in Figure 17. Responses in all cases are similar. Discrepancies can be accounted for by differences in the initiating and recovery inputs to roll stick. The flight record of roll angle differs from the BLFB in the time it takes to return to zero. This difference is attributable to the over-recovery indicated on the roll stick trace.

In the BHFB, the lag of the roll angle response of about 0.2 sec appears to be slightly greater than for the other cases, but the response is still very fast. In this case the roll angle continues to increase instead of returning to zero, but this action can be traced to the action of the roll stick, which does not recover completely and continues to feed a residual roll acceleration to the system.

Responses to step inputs in roll for the different simulators in hover are compared with flight in Figure 18. These responses appear to be excellent in all simulations. The amplitudes of roll rate and angle are in direct proportion to the size of the input, and the time to damp agrees well with flight. In all cases, the delay in roll angle response appears to be less than 0.2 sec. Comparable data for the BHFB simulation were not available.

Yaw Dynamics In Hover

Responses to rudder pedal step inputs for the different simulators in hover are compared with flight in Figure 19. The agreement among cases is actually very reasonable, although at first glance the results appear to be different. The discrepancies are explainable in terms of the limits of SAS authority in the yaw axis, which was 32 percent of maximum yaw control power in the aircraft, 24 percent in the ALMB, and unlimited in the BLFB. The SAS operates to drive yaw accelerations to zero in proportion to attitude rates within the limits of its control authority. Because SAS authority in the BLFB was unlimited, the result shown for the BLFB is a typically unsaturated SAS response. In the ALMB, the response shown is saturated, and the yaw rate is seen to continue its climb. In this case the input was sustained for only 3 sec, but if it could have been held longer, the rate would have gradually leveled off under the influence of aerodynamic damping. The difference in saturated and unsaturated SAS characteristics is compared directly by flight results for two different-size yaw control inputs. The saturated SAS input is the result of a pedal reversal maneuver rather than a step input, but the comparison shows the basic difference in response between saturated and unsaturated SAS cases and demonstrates the similarity of response between simulators and flight. For all maneuvers requiring less than the SAS saturation level (which includes most ordinary maneuvers), all simulators have similar dynamics and are directly comparable

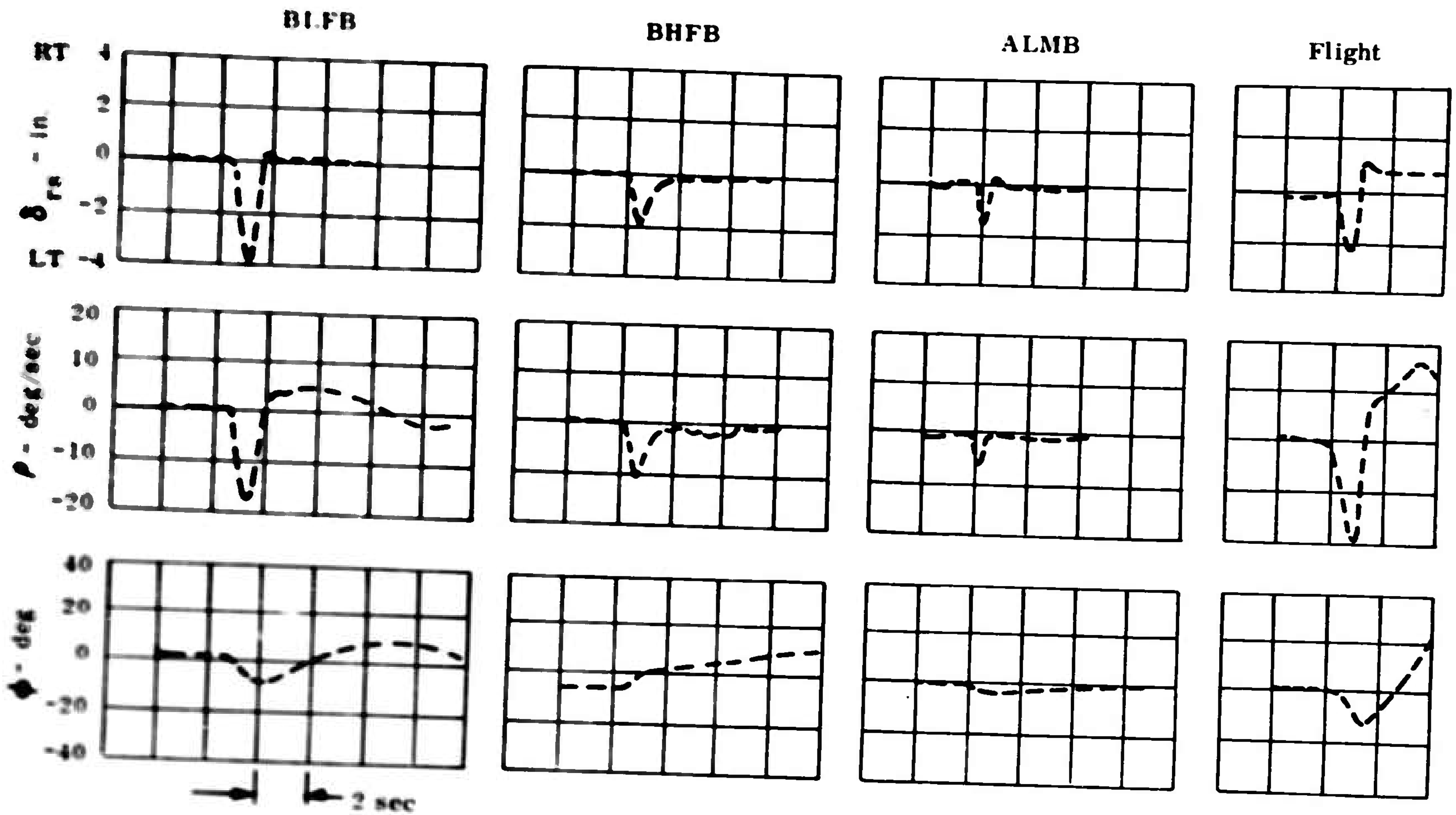

Figure 17. Comparison of Dynamic Response to a Pulse-Type Input of the Roll Control in Hover for Simulators and Flight.

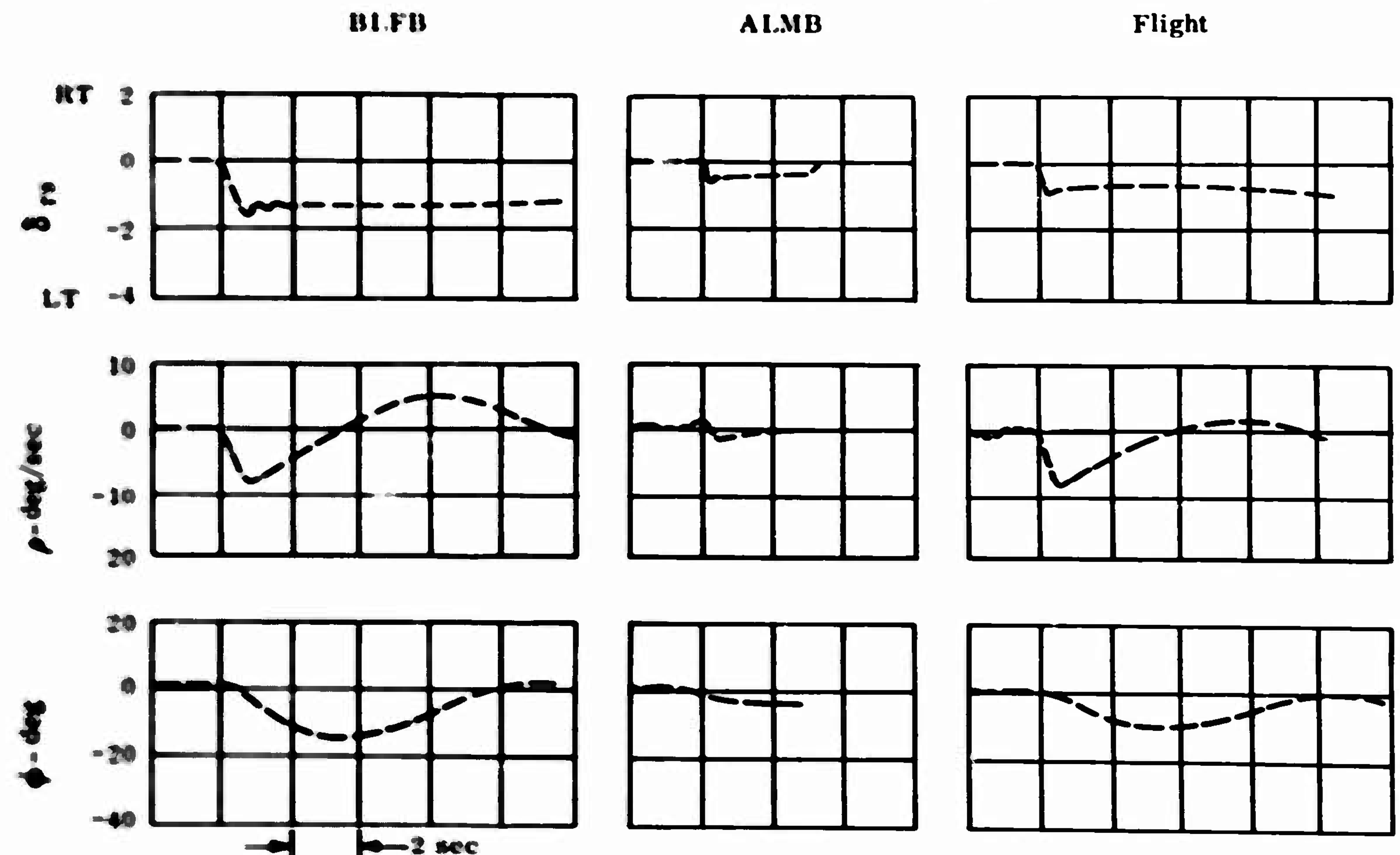

Figure 18. Comparison of Dynamic Response to a Step-Type Input of the Roll Control in Hover for Simulators and Flight .

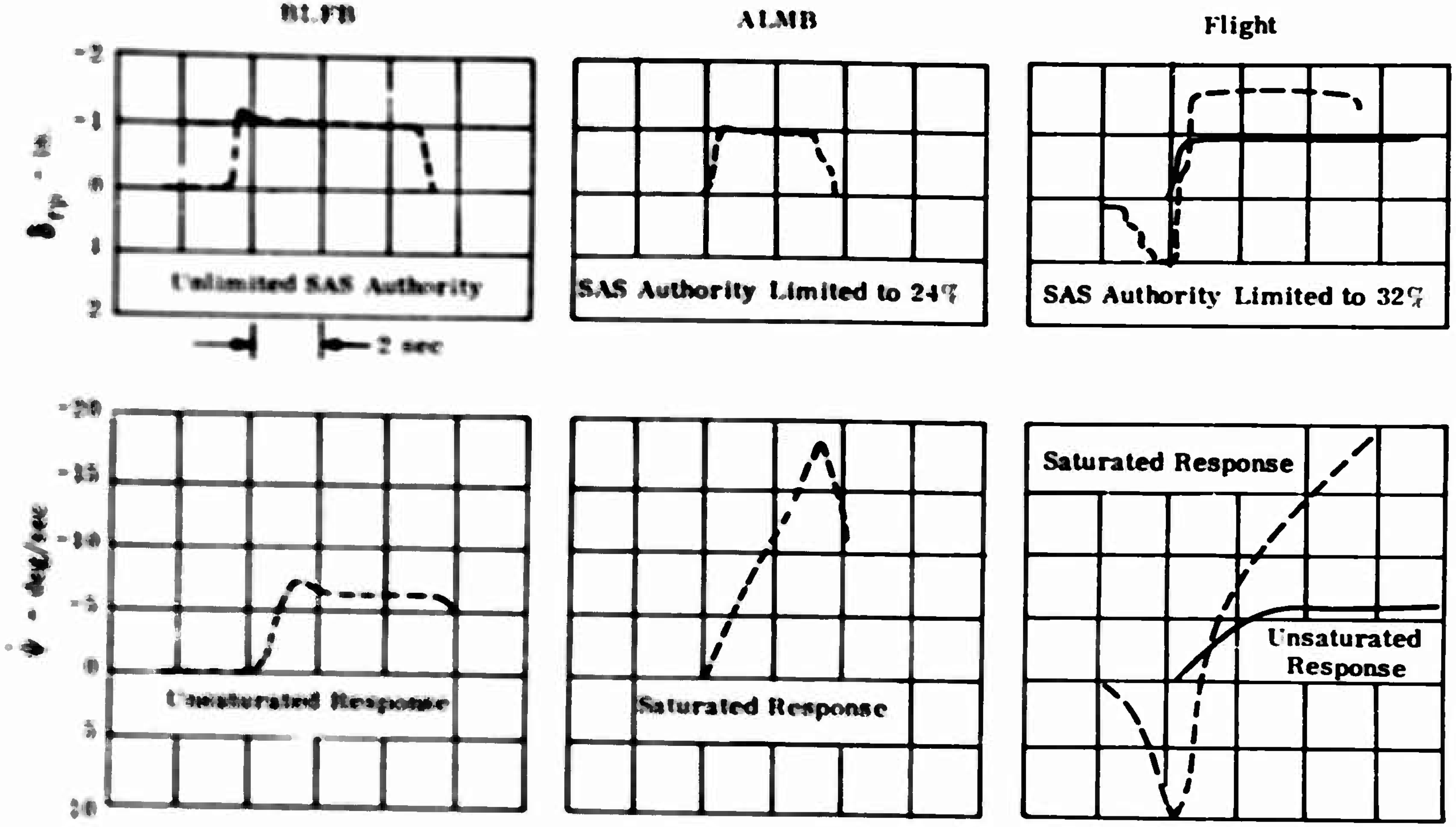

Figure 19. Comparison of Dynamic Response to a Step-Type Input of the Yaw Control in Hover for Simulators and Flight.

to the aircraft. Results agree with pilot comments and show that response is fast, with small inputs producing a rate response and large inputs producing an acceleration response. Accurate representation of these characteristics, which are most noticeable with motion simulation, requires mechanization of the limits of authority of the SAS. Comparable dynamic response time history data from the BHFB simulator were not available, but the characteristics were similar, and the yaw SAS authority was implemented at 24 percent.

Longitudinal Long-Period Dynamic Mode at Fixed Operating Points in Transition

Time history records of the long-period dynamic motion in the different simulators are compared with flight in Figure 20. The motion shown is an extended hands-off time interval starting from initial trim at $\lambda = 30^\circ$, V = 80 kn. Since the task was hands-off, stick position was constant and is not shown.

The mild divergence of the long-period mode, which is characteristic of the aircraft, is shown to be well represented in all simulators. In the ALMB, the presence of an initial rate of climb, $\dot{h}$, explains the difference between the altitude traces. The faster rates of response obtained in the BLFB were caused by control inputs at the beginning of the maneuver, which are evident in the pitch attitude, θ, and the rate of climb, $\dot{h}$, traces. At other duct angles and trim speeds, the simulations were equally comparable with flight. The rate of divergence of the long-period mode has a gradually decreasing trend with increasing duct angle and decreasing speed. At 60° duct angle and approximately 45 kn, the stability appears to be neutral. With reduced SAS or at speeds away from trim, the rate of divergence is increased.

Longitudinal Short-Period Dynamic Mode at Fixed Operating Points in Transition

Time history records of the short-period dynamic response to step-type pitch control inputs, in the different simulators and in flight, are compared in Figure 21. Motion characteristics are shown to be similar for all cases. Rate response to the control input is very fast, highly damped, and in proportion to the size of the control input, as measured from the initiation of the control motion to the peak of the rate response trace. The rest of the time history shows the residual steady pitch rate which follows the short period and which is established as a result of the sustained control input. Differences in the magnitude of the residual steady pitch rate and in the development of the pitch attitude trace, relative to the size of the control inputs for the different simulator cases compared to flight, can be explained in terms of the pitching moment equation, which for a constant pitch rate reduces to

$$M_{\delta_{ps}} \delta_{ps} + M_w w + M_u u + M_q q = 0 \qquad (120)$$

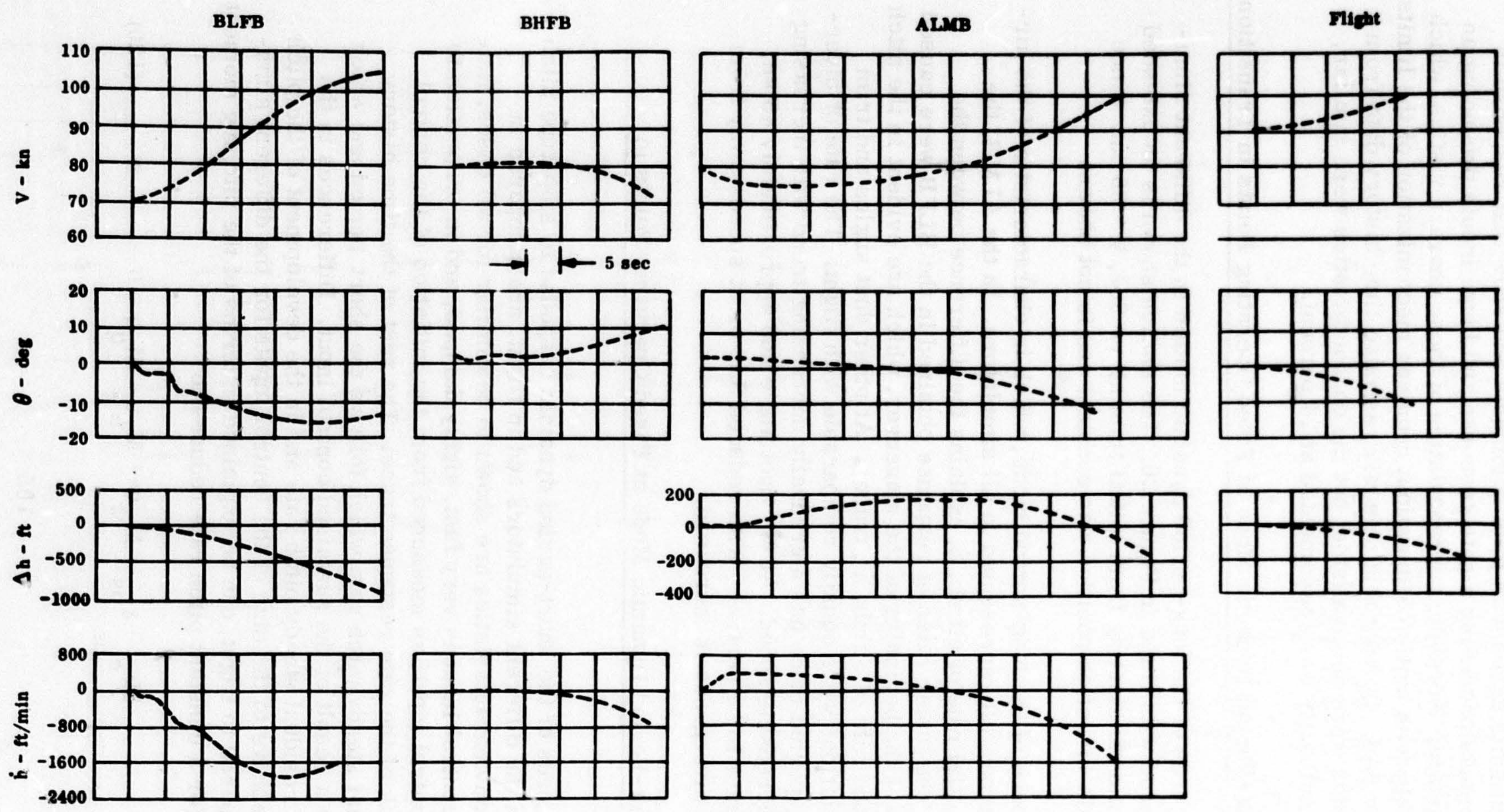

Figure 20. Comparison of Control-Free Dynamic Response for the Long-Period Dynamic Mode in Fixed Operating Point Transition (λ = 30°, V = 80 kn).

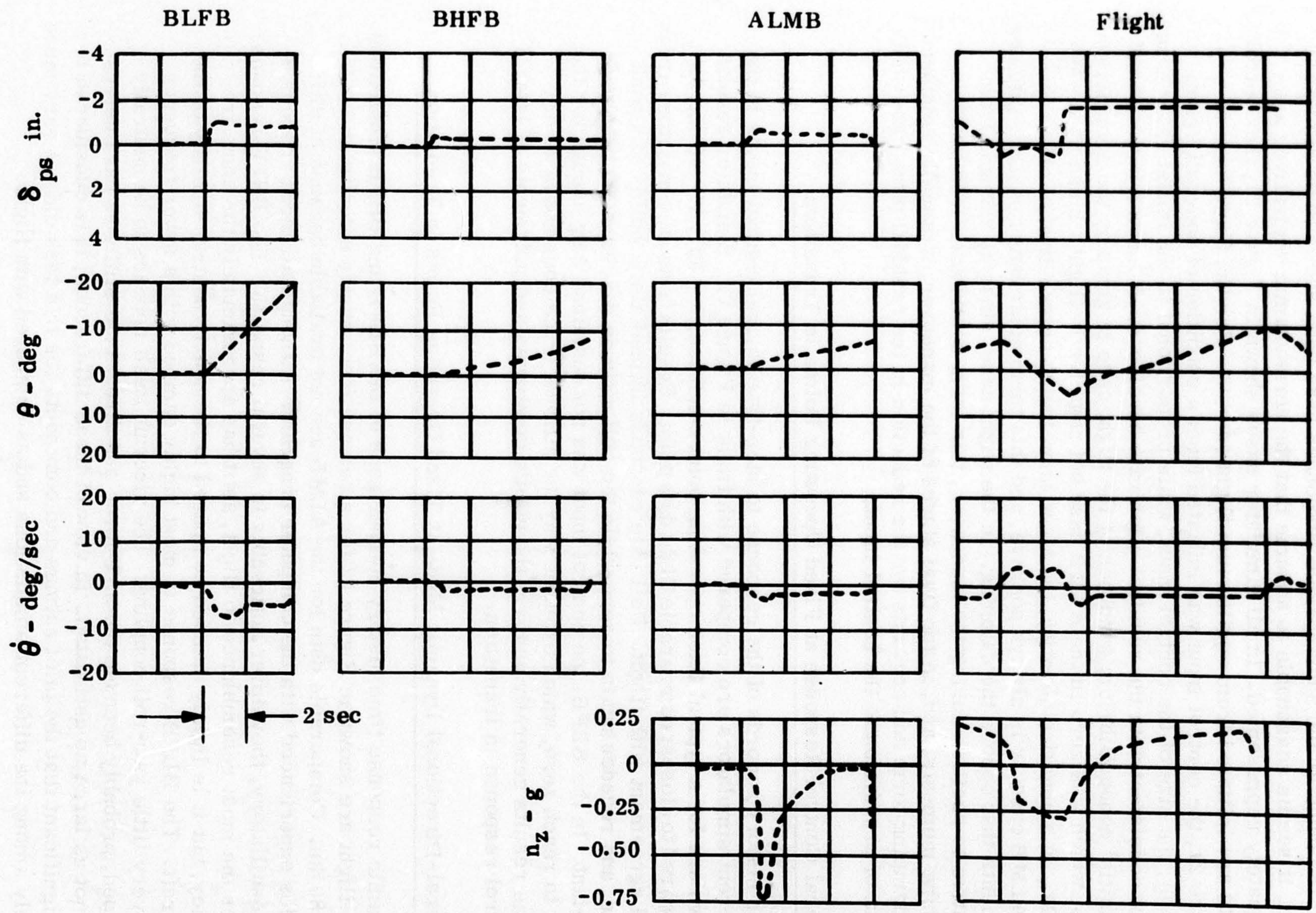

Figure 21. Comparison of Dynamic Response to a Step-Type Input of the Pitch Control for Fixed Operating Point Transition ($\lambda = 30^\circ$, V = 80 kn).

Since the phugoid and short-period responses have been shown to be similar to flight, it seems reasonable to assume that the aerodynamic derivatives are adequately represented. In all simulator cases shown in Figure 21, the control inputs are initiated from equilibrium flight ($\dot{\theta}$ = 0). For the flight case of Figure 21, the control input was initiated from a condition of nonequilibrium ($\dot{\theta} \neq 0$); the size of the control input, while proportional to the initial rate change, is not consistent with the residual pitch rate developed. A further indication of the initial nonequilibrium condition of the flight case is given by the comparison of n_z, which was zero in the ALMB case but negative in flight. Since $n_z = -\frac{dw}{dt}$ and M_w is a negative quantity, the $M_w w$ term has the opposite sign of w. In the ALMB case, w is always positive, and this term contributes positive pitching moments that oppose the damping. In the flight case, since n_z changes from negative to positive during the maneuver, this term contributes less positive pitching moments, and, in the final stages of the maneuver, it actually reinforces the damping term and accounts for the reduction in the residual pitch rate which is out of proportion to the control input.

Lateral Control Response at Fixed Operating Points in Transition

Time history records of the response to step-type lateral control inputs in the different simulators are compared with flight in Figure 22. Simulator results shown are for a typical fixed operating point condition, $\lambda = 30°$, V = 80 kn, as compared to closest comparable flight data point. Results from all simulators are in good agreement with flight. Roll rate responds immediately, builds to a peak value, and recedes again to zero while the roll attitude develops and becomes constant. In the BLFB, the control input was not sustained long enough for the rate to reach zero, which explains why the attitude trace does not level off. These results generally confirm the pilot's comments and judgments of lateral control response in transition.

Lateral-Directional Dynamic Mode at Fixed Operating Points in Transition

Dynamic response time history comparisons of the BLFB and BHFB simulators with flight are shown in Figure 23 for a release from steady sideslip at $\lambda = 30°$, V = 80 kn. Comparable data for the ALMB are not available because of difficulties experienced with the computer program. Although all three responses are oscillatory, they differ noticeably in several respects. The BHFB response bears the most resemblance to flight, as it has approximately the same frequency, but it is lightly damped compared to the nearly neutral stability of the aircraft. The BLFB response is most highly damped with a lower frequency and very little yaw-roll coupling. The aircraft itself appears to be neutrally damped, probably because the side force and directional stiffness parameters are not as large as estimated. In view of these differences, it is considered to be significant that the pilot ratings and comments for this task did not vary more widely among the different simulations and as compared with flight.

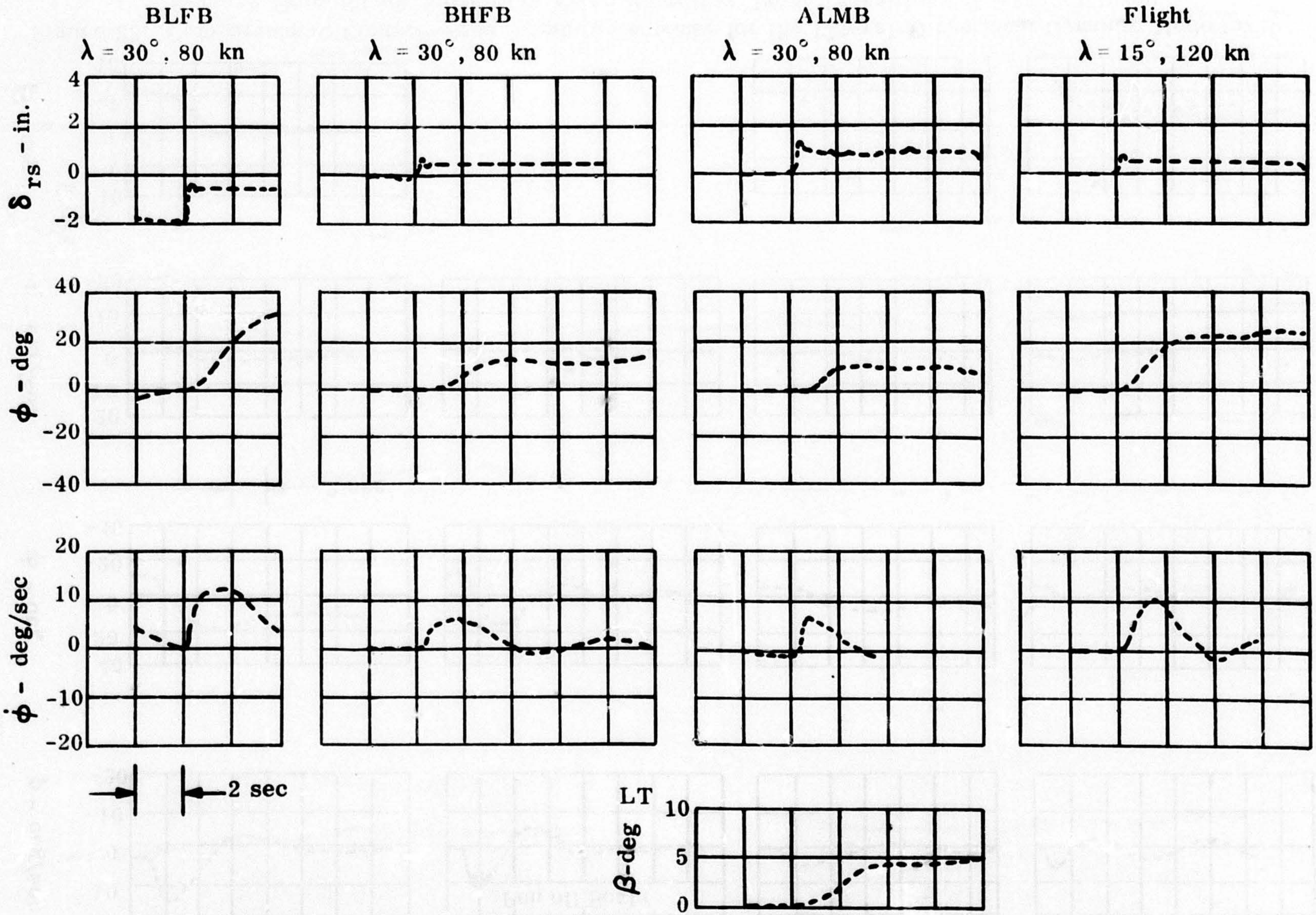

Figure 22. Comparison of Dynamic Response to a Step-Type Input of the Roll Control for Fixed Operating Point Transition.

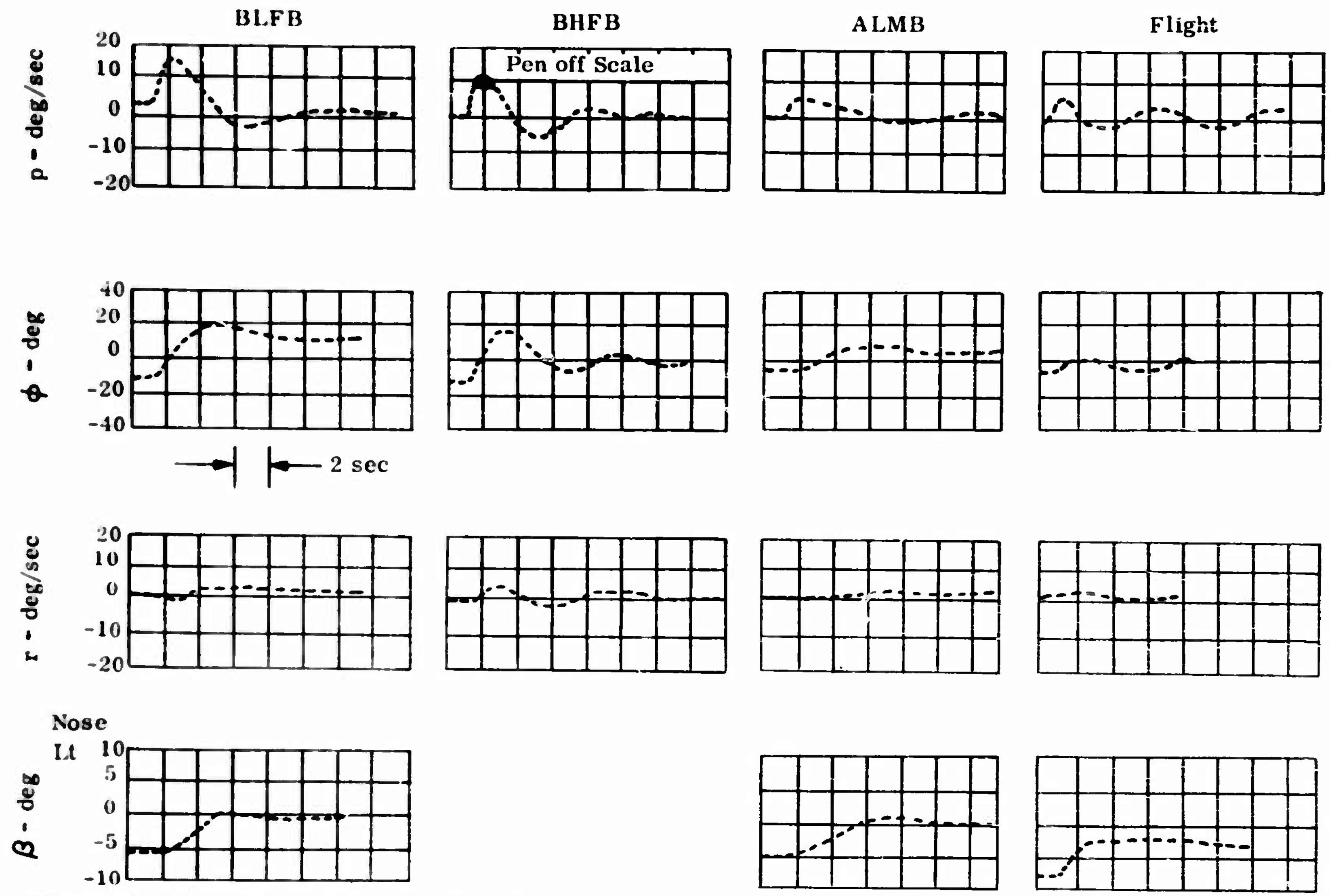

Figure 23. Comparison of Control-Free Dynamic Response for the Lateral-Directional Dynamic Mode for a Release From Steady Sideslip in Fixed Operating Point Transition (λ =30° , V = kn).

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13. ABSTRACT

Three types of ground-based simulators of the X-22A aircraft are evaluated and compared with actual flight. Simulator types employed were a fixed-base simulator with linearized equations of motion, a fixed-base simulator with nonlinearized equations of motion, and a moving-base simulator with linearized equations of motion. Evaluations are based on comparisons of pilot ratings, pilot comments, and dynamic response time history data. Data comparisons are interpreted and discussed in terms of significant factors such as simulator type, complexity, and physical and psychological cues.

Several correlations among the different simulators and flight are developed in terms of numerical pilot ratings of specific flight conditions and tasks. These pilot rating correlations provide a basis for projecting flight characteristics from results obtained with the simulator types evaluated. Relative capabilities and limitations of the various simulators to represent flight and minimum standards of adequacy for specific tasks are also established for hover and transition.

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